16th July 2021
Seminar at TITECH

Intrinsic alignment of galaxies as a novel probe of cosmology

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Plan of talk

The intrinsic alignment (IA) of galaxies as a novel probe of precision cosmology

Introduction & motivation

Modeling intrinsic alignment signals

Forecast for cosmological constraints

Summary

Refs.

T. Okumura & A. Taruya & T. Nishimichi, MNRAS 494, 694-702 ('20)

A. Taruya & T. Okumura, ApJL 891, L42 ('20)

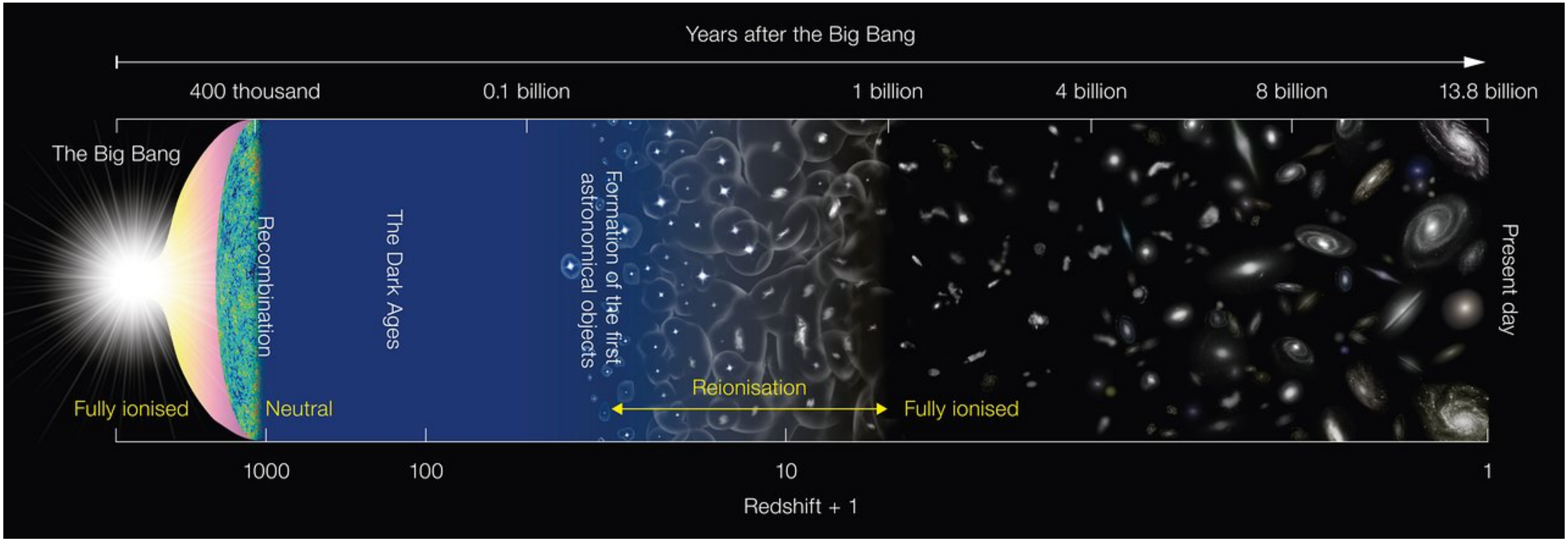
T. Okumura & A. Taruya, MNRAS 493, L124-L128 ('20)

Concordant picture of the Universe

<u>Lambda cold dark matter (ΛCDM) model</u>

Minimal model characterized by 6 parameters

Model describes both cosmic expansion and structure formation over *13.8* billion years



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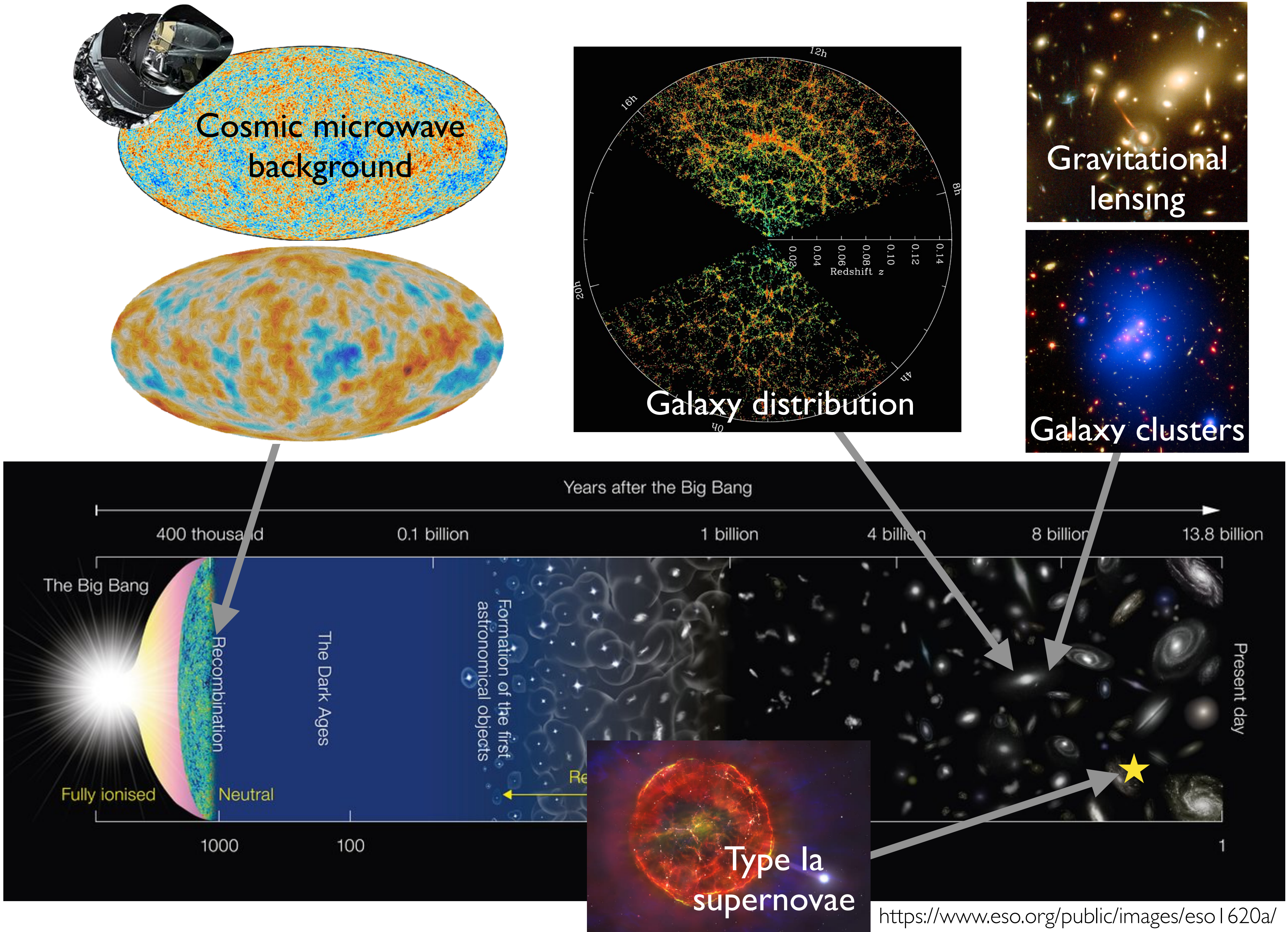
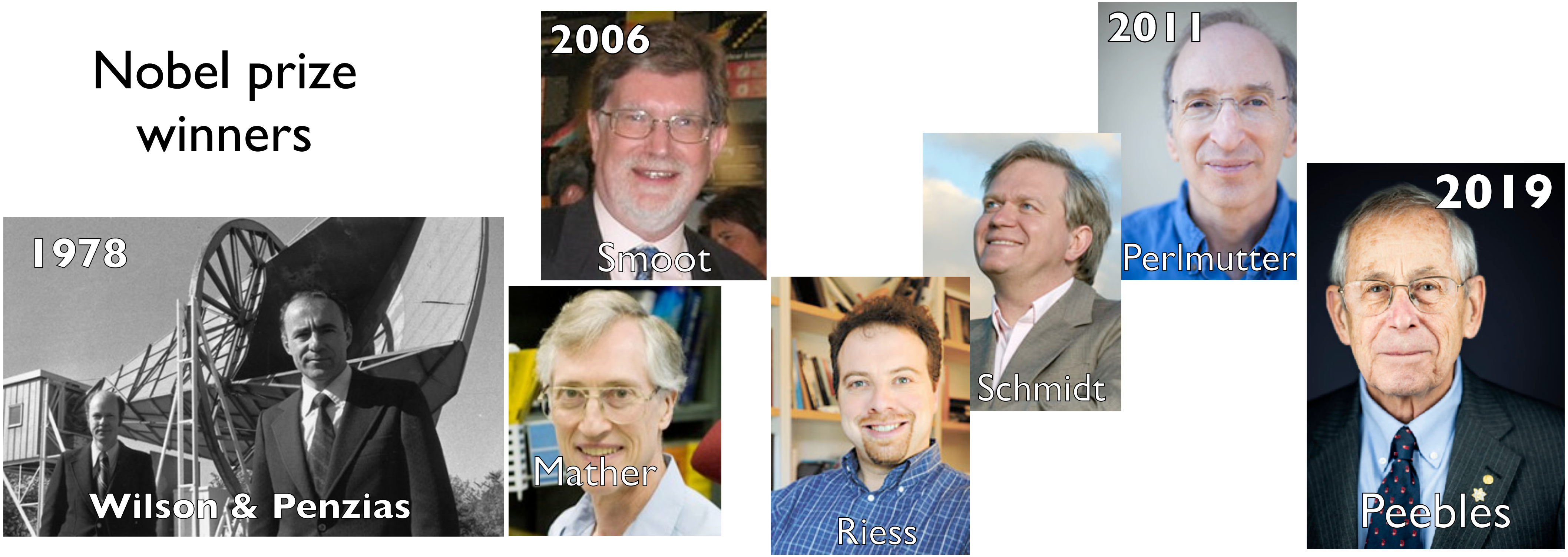
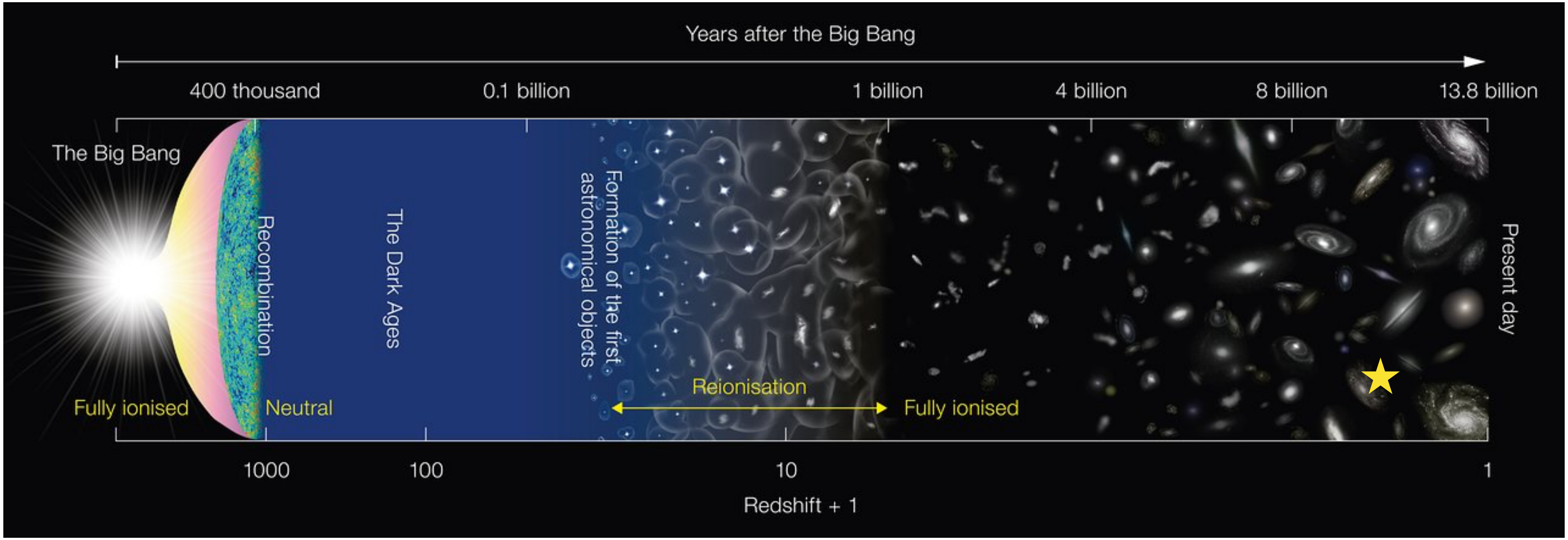

Cosmic microwave background
Galaxy distribution
12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
Gravitational lensing
Galaxy clusters
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Neutral
1000
100
1
Type Ia supernovae
https://www.eso.org/public/images/eso1620a/

Nobel prize winners

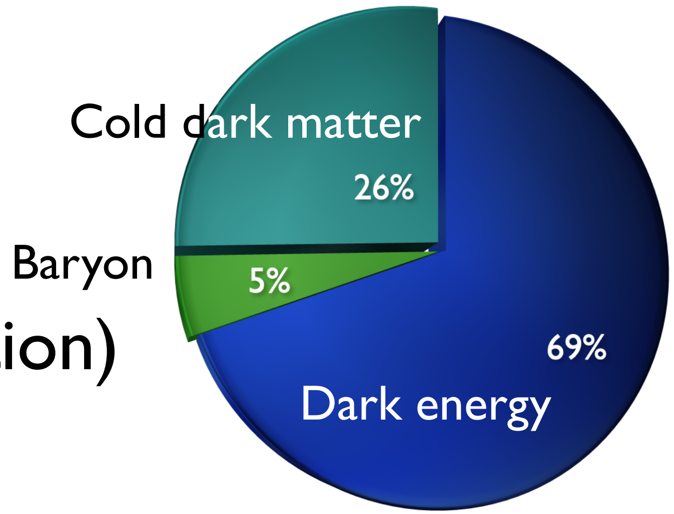




https://www.eso.org/public/images/eso1620a/

Unresolved issues

Success of minimal model does not imply model is convincing



Mysterious components

Dark matter

Dark energy (late-time cosmic acceleration)

Untested hypothesis

Cosmic inflation

General relativity on cosmological scales

Gaussianity of primordial fluctuations

Tension

Discrepancy of Planck ΛCDM model parameters with those obtained from other observations (H_0, S_8, …)

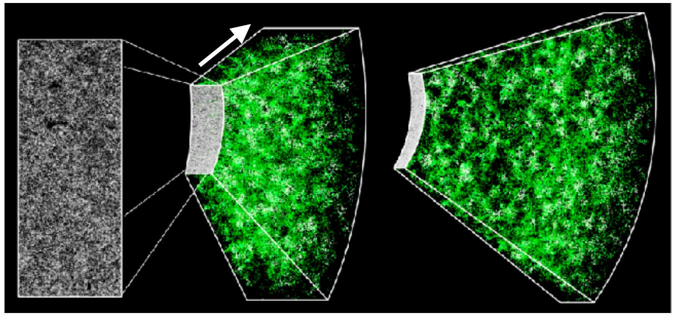
Large-scale structure

Large-scale matter inhomogeneities over Mpc~Gpc scales

evolved under the influence of gravity & cosmic expansion

Its statistical nature carries rich cosmological information

Using (mainly) galaxies as a tracer of LSS,



✓ Photometric/imaging surveys
(angular position + galaxy shape)

Weak lensing effect

✓ Spectroscopic surveys
(angular position + redshift)

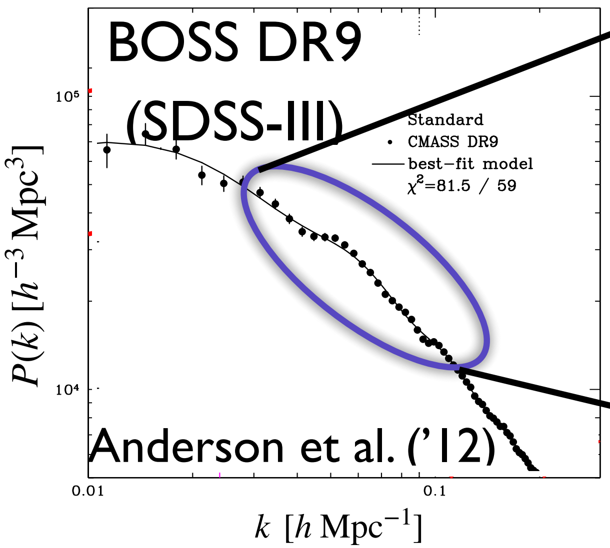
Baryon acoustic oscillation (BAO)

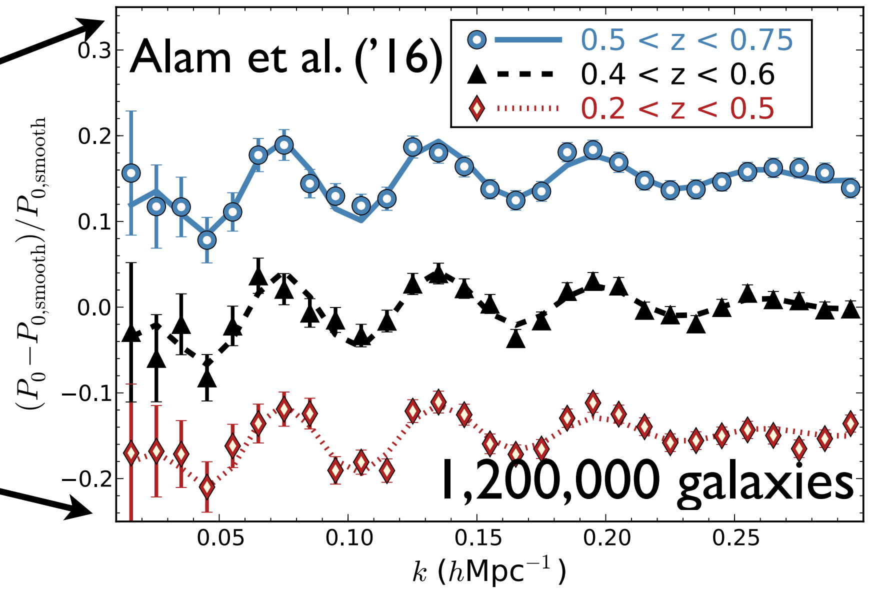
Redshift-space distortions (RSD)

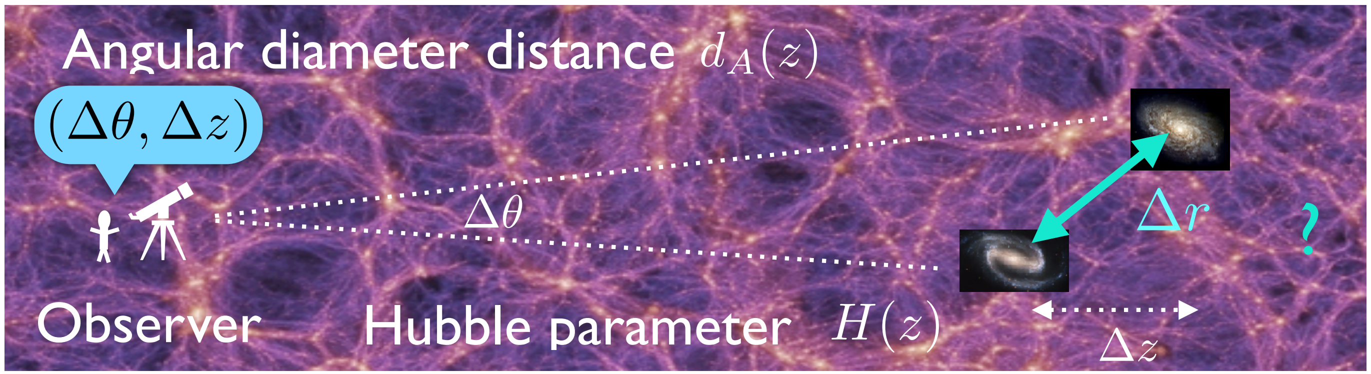
Baryon acoustic oscillations (BAO)

Characteristic oscillatory features of primeval baryon-photon fluid imprinted on galaxy clustering pattern at ~100Mpc

→ BAO scale can be used as a standard ruler







Cosmological dependence

$$\Delta r_{\parallel} = \{c/H(z)\}\,\Delta z$$

$$\Delta r_{\perp} = d_A(z)\,\Delta\theta$$

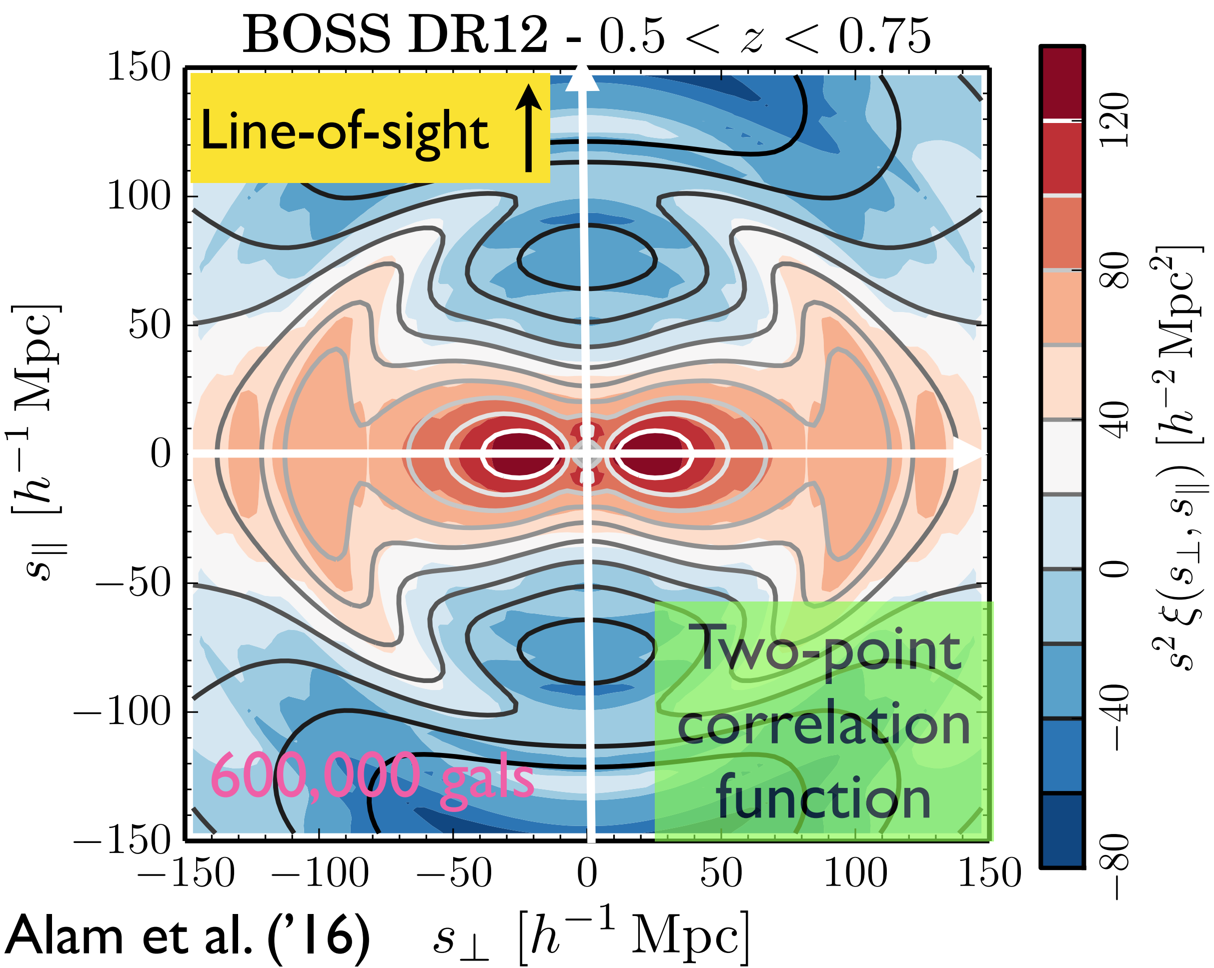
Redshift-space distortions (RSD)

Apparent distortions of galaxy line-of-sight position due to peculiar velocity of galaxies via Doppler effect

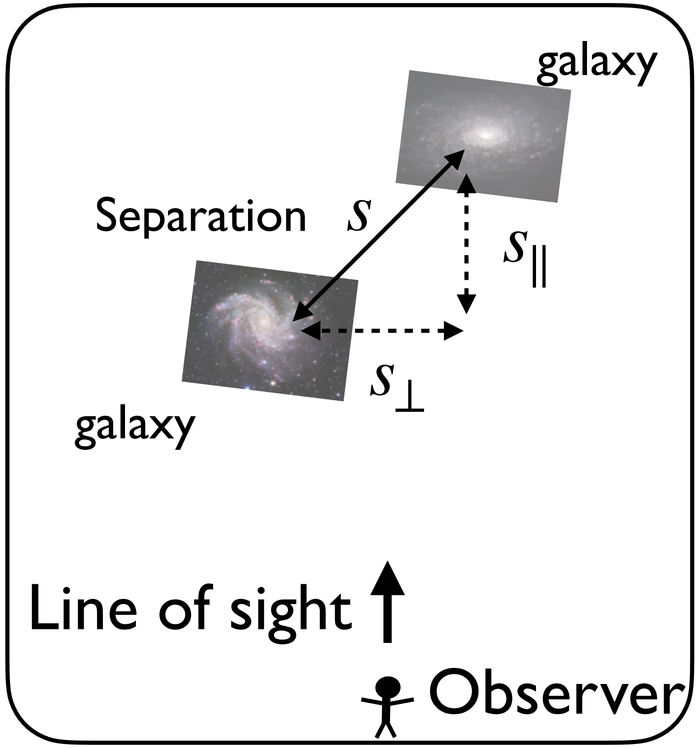
⟶ Strength of anisotropies depends on growth of structure

$$f\sigma_8(z) = \frac{d\ln D}{d\ln a}\sigma_8(z) \quad \text{(Kaiser '87)}$$

$$\to \Omega_\mathrm{m}(z)^{0.6}\sigma_8(z) \quad \text{(GR)}$$

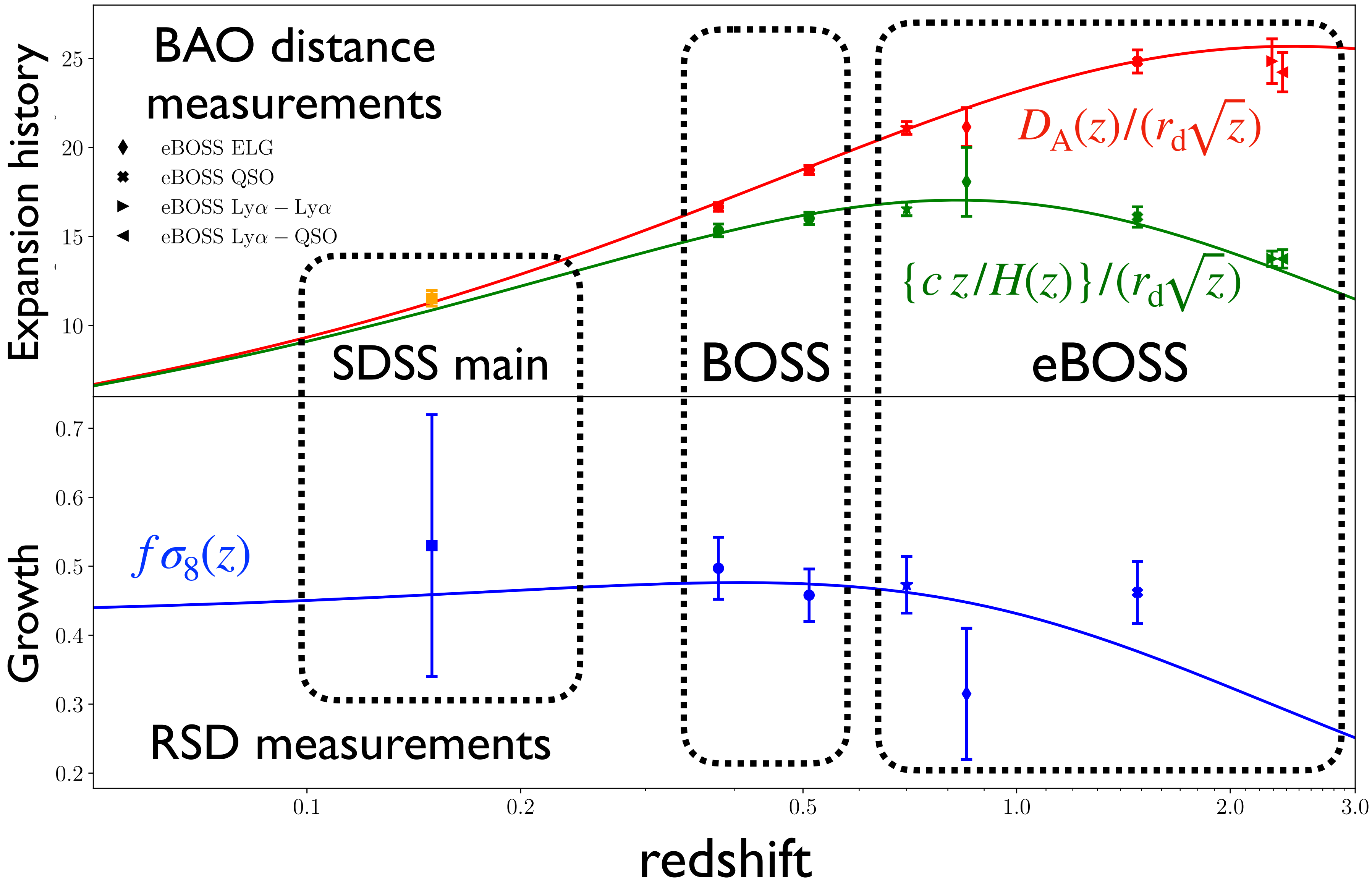


Alam et al. ('16)



Constraints from BAO & RSD

Alam et al. ('20)

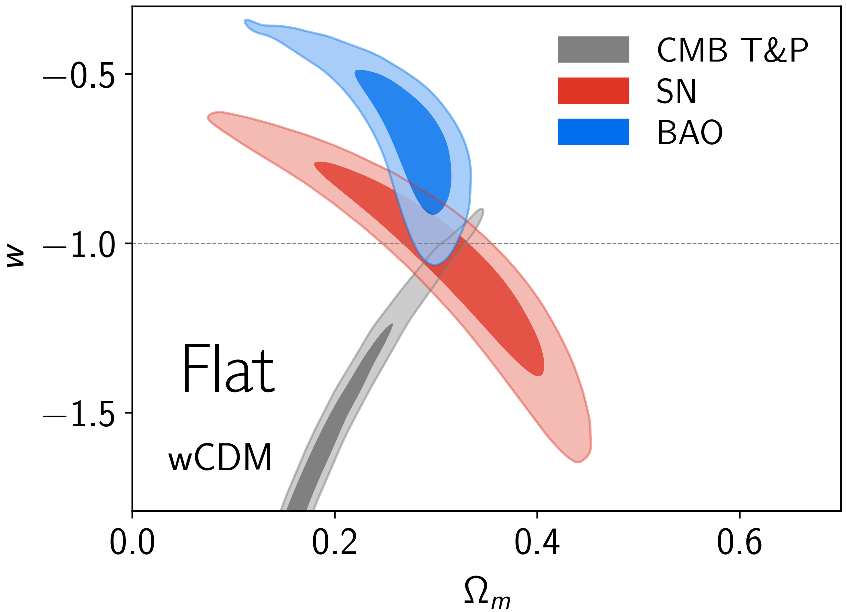


arXiv:2007.08991

Cosmological constraints

Alam et al. ('20)

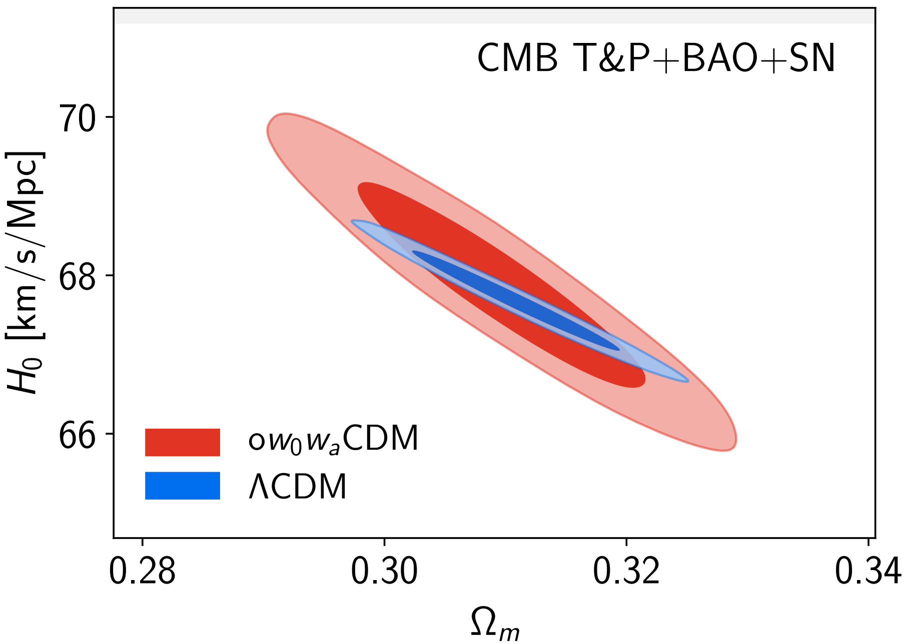
arXiv:2007.08991

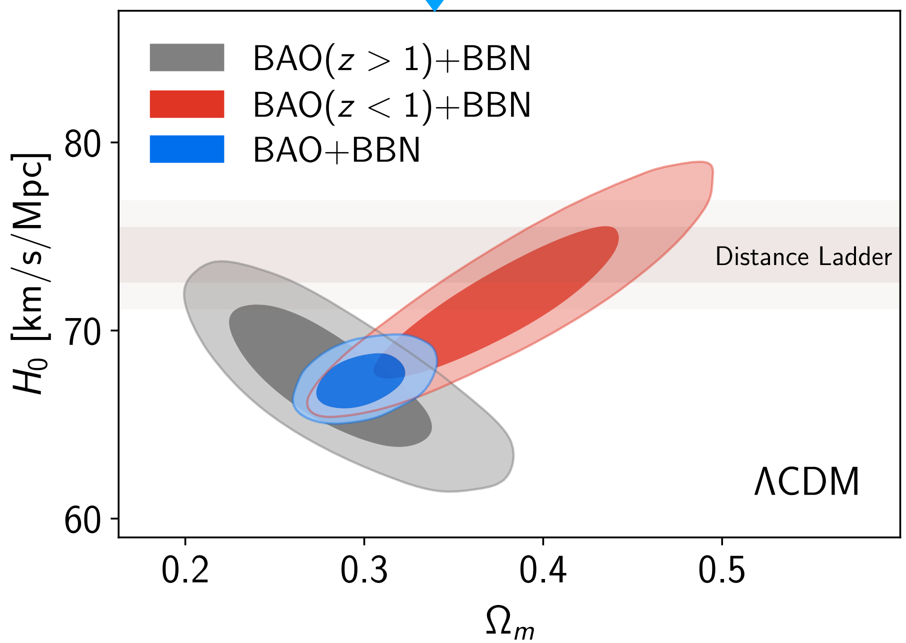


Dark energy equation-of-state

$$P_{\rm DE} = w\,\rho_{\rm DE}$$

Hubble parameter

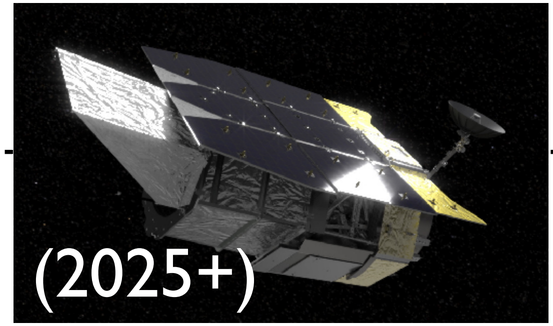




Ongoing/upcoming surveys

From stage III to stage IV-class surveys (ground & space)

Imaging surveys

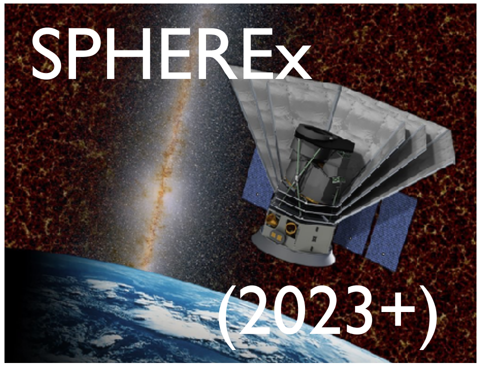


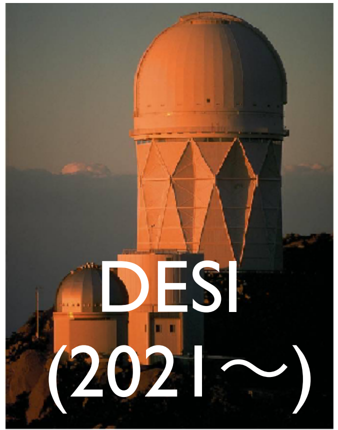
Nancy Grace Roman Space Telescope (WFIRST)

HSC
(2014~)

PFS
(2023~)

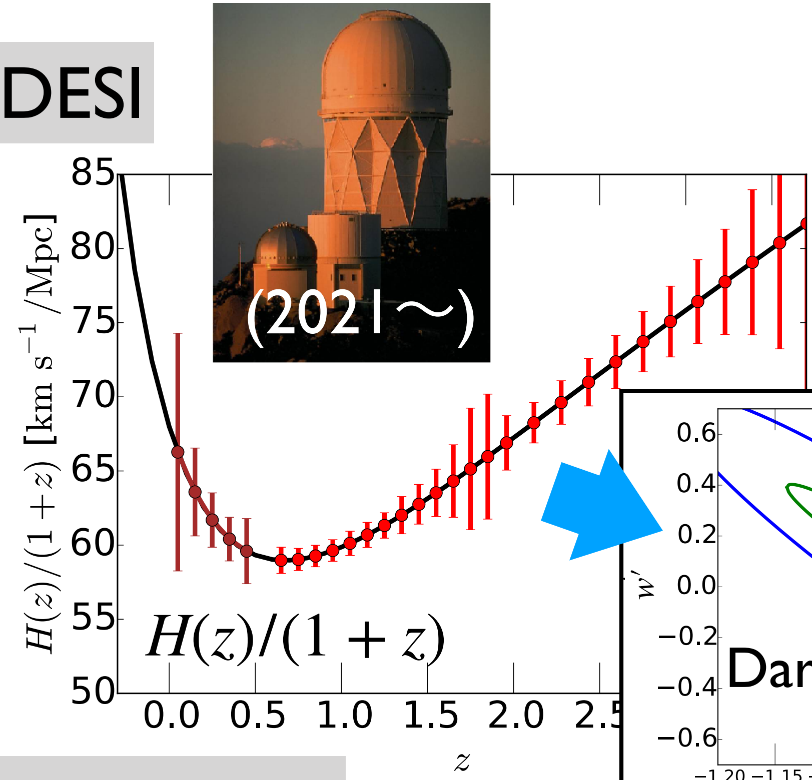
Spectroscopic surveys

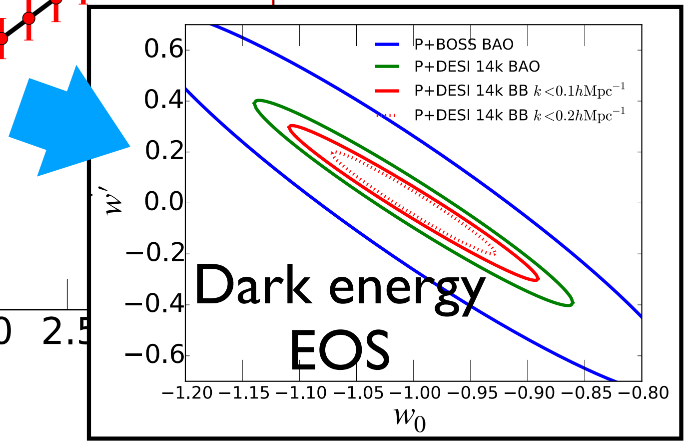




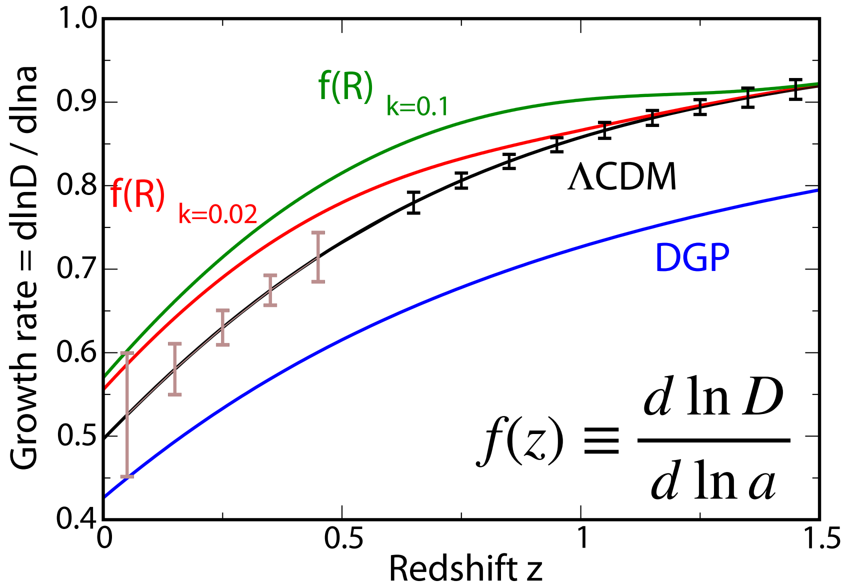
Future

DESI

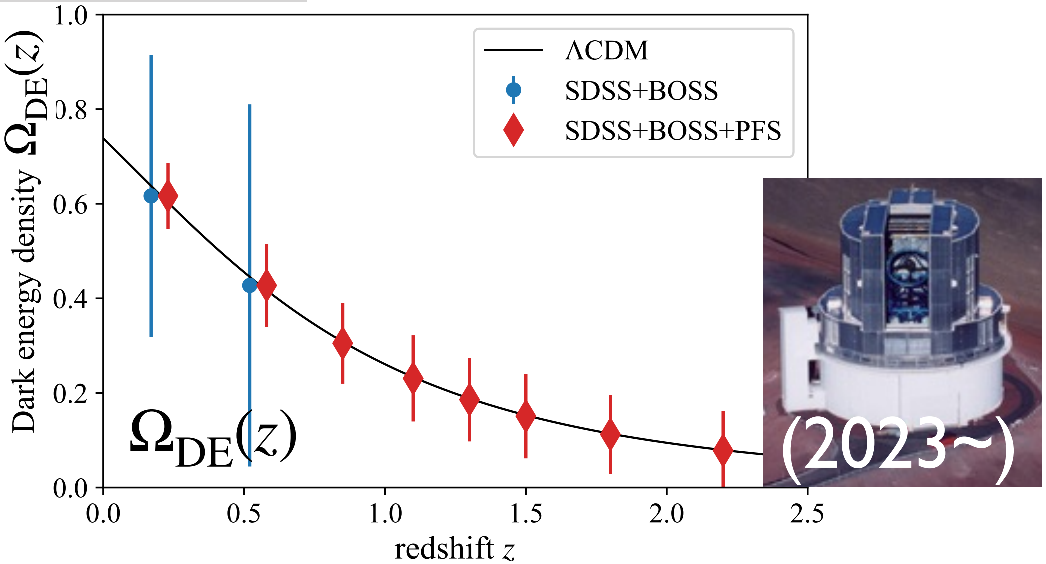




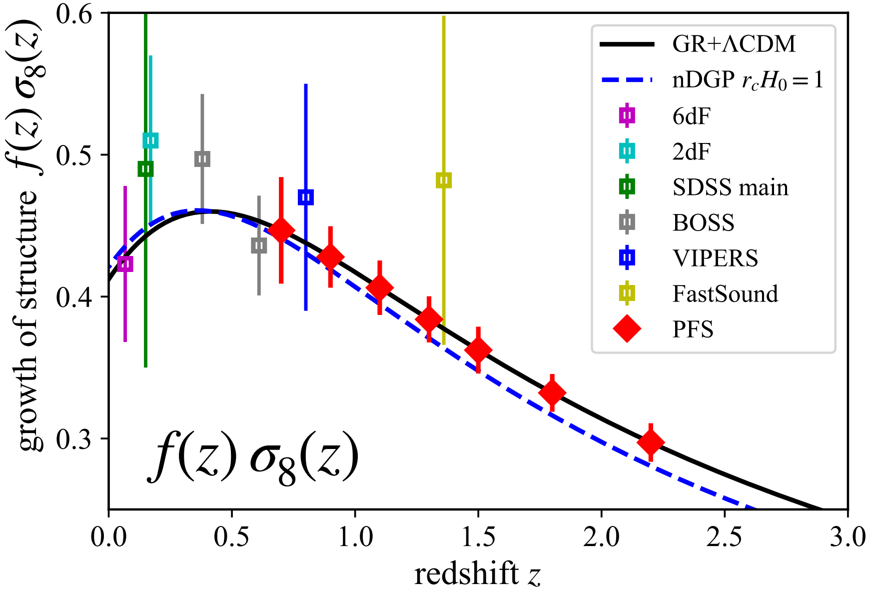
arXiv:1611.00036



Subaru PFS



Subaru SSP



Improving cosmological constraints

Toward a better cosmological constraints,
without conducting extra surveys

Pushing available Fourier modes to a larger value $k_{\rm max} \nearrow$ (small scales)

Theoretical modeling far beyond linear regime is challenging

Using technique/method that maximizes cosmological information :

Combining several statistics such as bispectrum

Cross correlating multiple data set,
also utilizing the information that has been abandoned

Improving cosmological constraints

Toward a better cosmological constraints,

without conducting extra surveys

Pushing available Fourier modes to a larger value $k_{\rm max} \nearrow$ (small scales)

Theoretical modeling far beyond linear regime is challenging

Using technique/method that maximizes cosmological information :

Combining several statistics such as bispectrum

Focus of this seminar

Intrinsic alignment (IA) of galaxies as a cosmological probe

Statistical properties of *3D correlations*

& cosmological information

Intrinsic alignment (IA) of galaxy

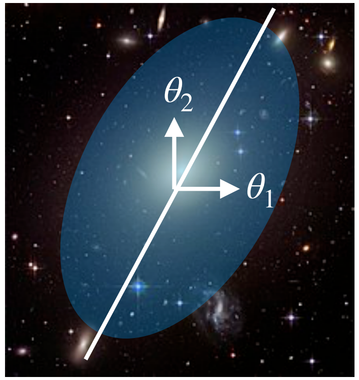
Projected shape of observed galaxies/dark matter halos

In general, galaxy/halo has elliptical shape, aligned to some directions:

Quadrupole moment of galaxy image

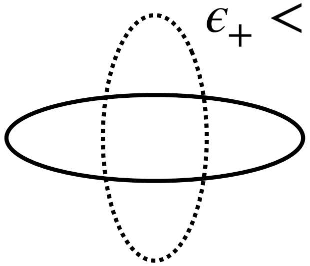
$$q_{ij}^{\rm obs} \equiv \frac{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})\, \theta_i \theta_j}{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})} \quad (i, j = 1,2)$$

intensity



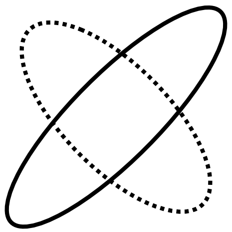
Ellipticity：

$$\epsilon_+ \equiv \frac{q_{11}^{\rm obs} - q_{22}^{\rm obs}}{q_{11}^{\rm obs} + q_{22}^{\rm obs}}, \qquad \epsilon_\times \equiv \frac{2q_{12}^{\rm obs}}{q_{11}^{\rm obs} + q_{22}^{\rm obs}}$$



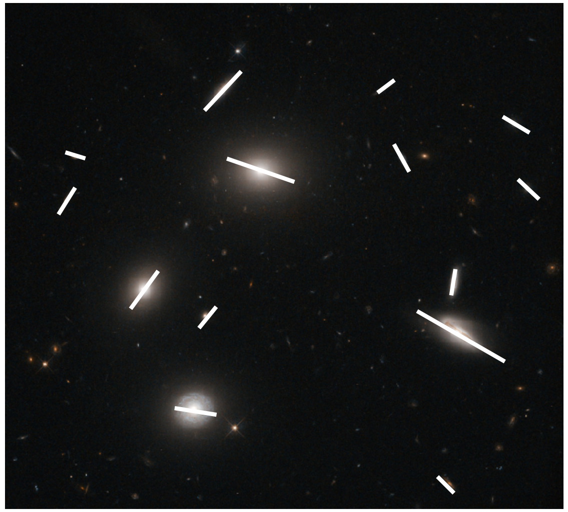
$\epsilon_+ < 0$

$\epsilon_+ > 0$



$\epsilon_\times > 0$

$\epsilon_\times < 0$



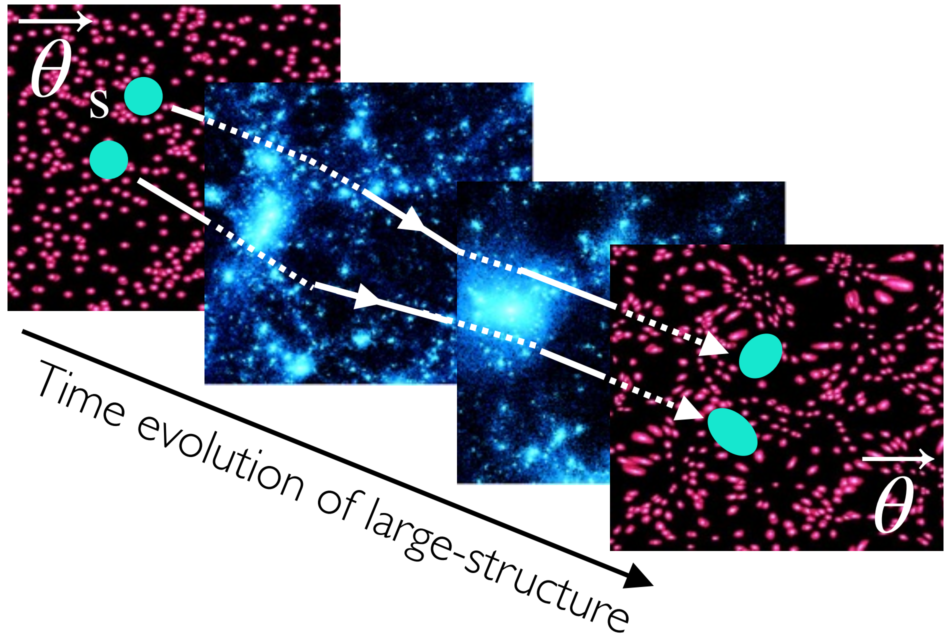
Intrinsic alignment (IA) of galaxy

Ellipticity of distant galaxy is induced by the gravitational lensing of foreground large-scale structure :

$$\epsilon_a \simeq \gamma_a^{\rm I} + 2\, g_a \; ; \qquad g_a \equiv \frac{\gamma_a}{1-\kappa} \, (\ll 1)$$

$(a = + \text{ or } \times)$ Reduced shear

IA Lensing



Gravitational lensing induces non-zero spatial correlation

⟶ A clue to detect lensing signal

However,

IA can have non-zero spatial correlation

(contaminant of lensing measurement)

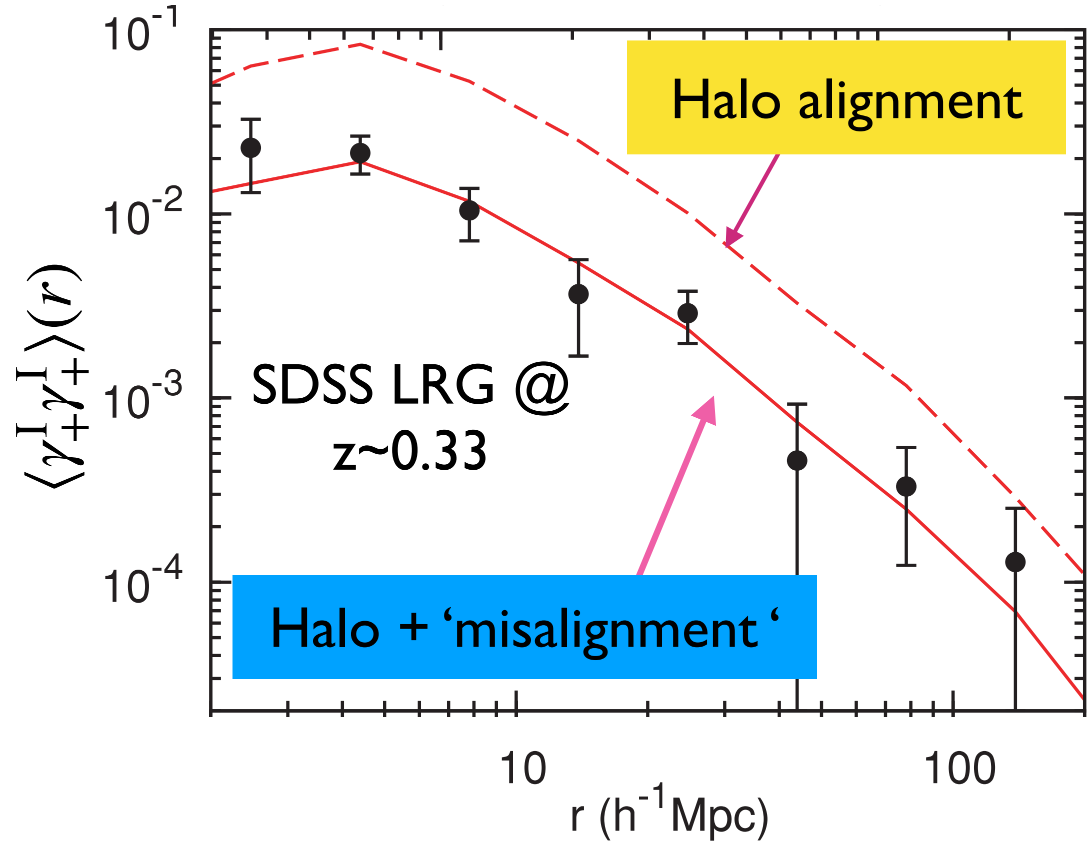
Troxel & Ishak ('15)

Joachimi et al. ('15)

Intrinsic alignment (IA) correlation

3D spatial correlation of luminous red galaxy (LRG) samples

angular position (2D) + redshirt + shape



Early type

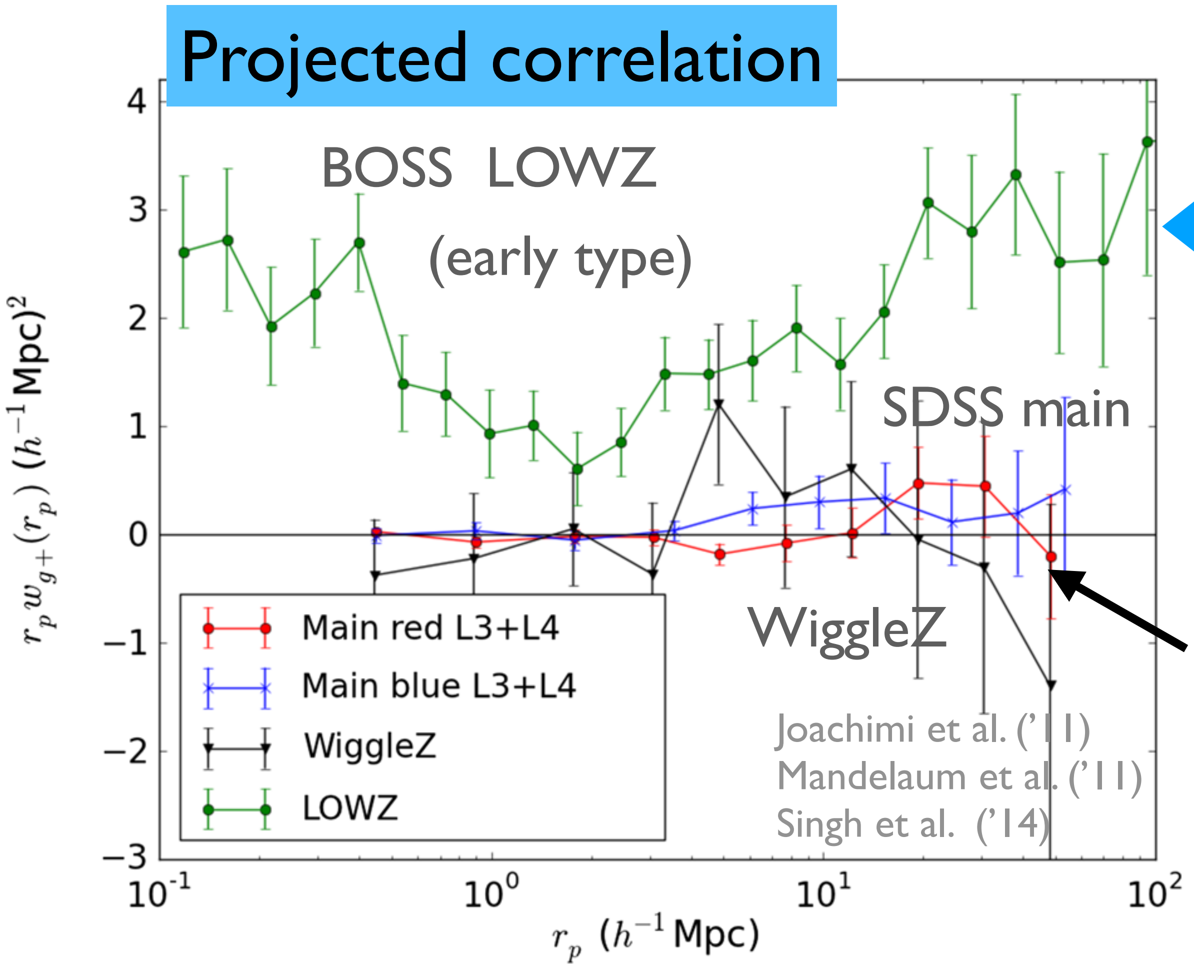
$\langle \gamma_+^I \gamma_+^I \rangle$ (II correlation)

Okumura, Jing & Li (’09)

Measured result resembles the halo ellipticity correlation in N-body simulations (solid & dashed lines)

Intrinsic alignment (IA) correlation

Behaviors of IA correlation crucially depend on galaxy type



Galaxy-IA correlation

(GI correlation)

$$\langle \delta_{\rm g} \gamma_+^{\rm I} \rangle$$

No clear correlation signal is detected for late-type galaxies

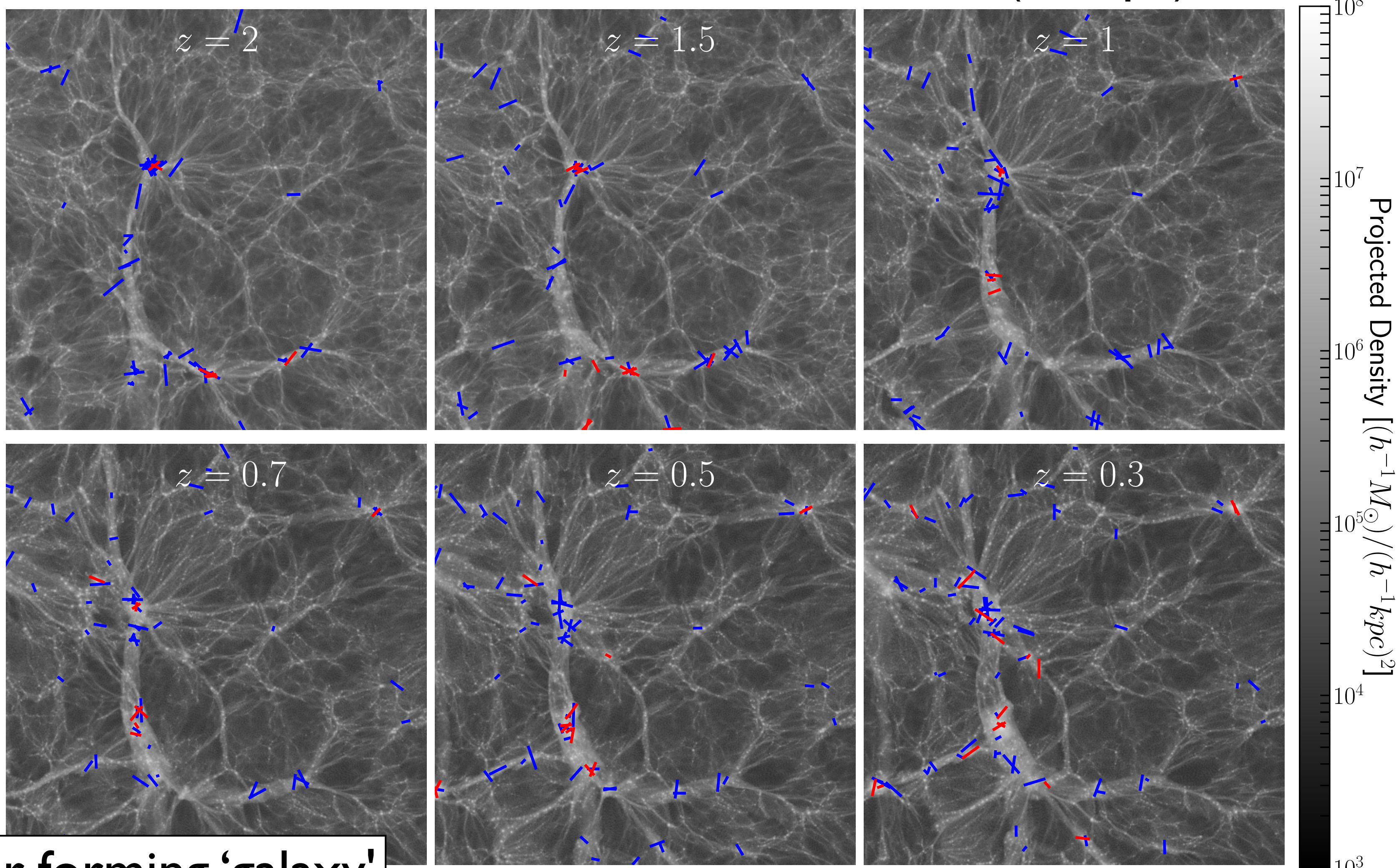
Joachimi et al. ('15)

IA in hydrodynamic simulations

Illustris-TNG300

40 x 40 $(h^{-1}\mathrm{Mpc})^2$

Shi et al. ('20)



Blue: star-forming 'galaxy'

Red: quiescent 'galaxy'

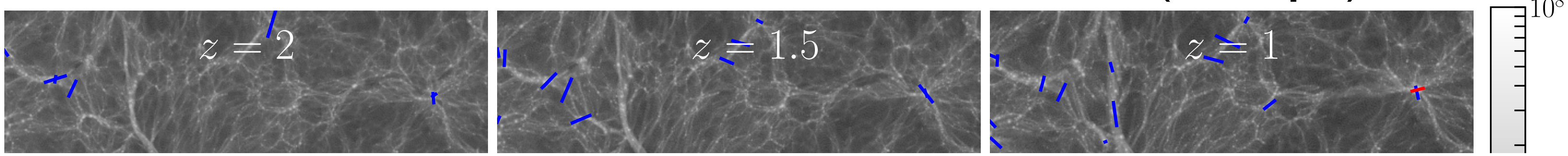
Blue seems to be randomly oriented

IA in hydrodynamic simulations

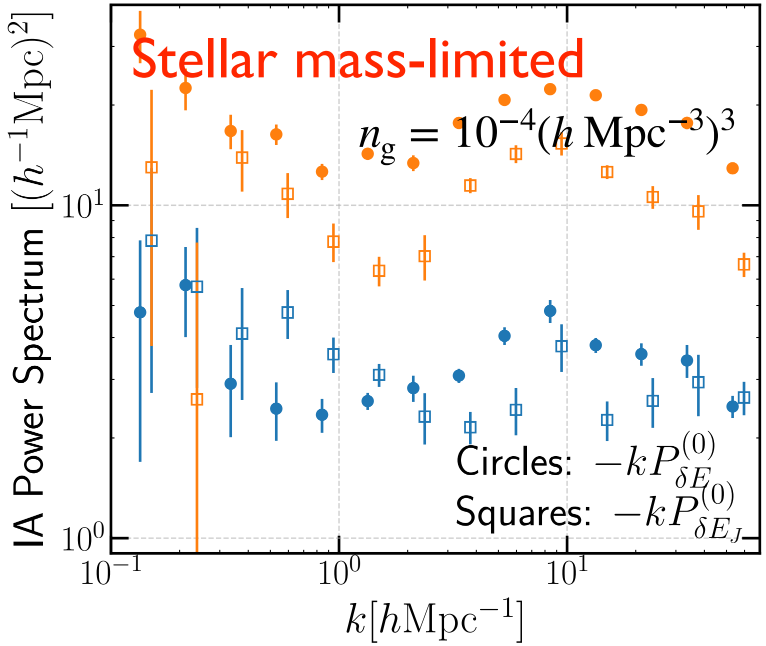
Illustris-TNG300

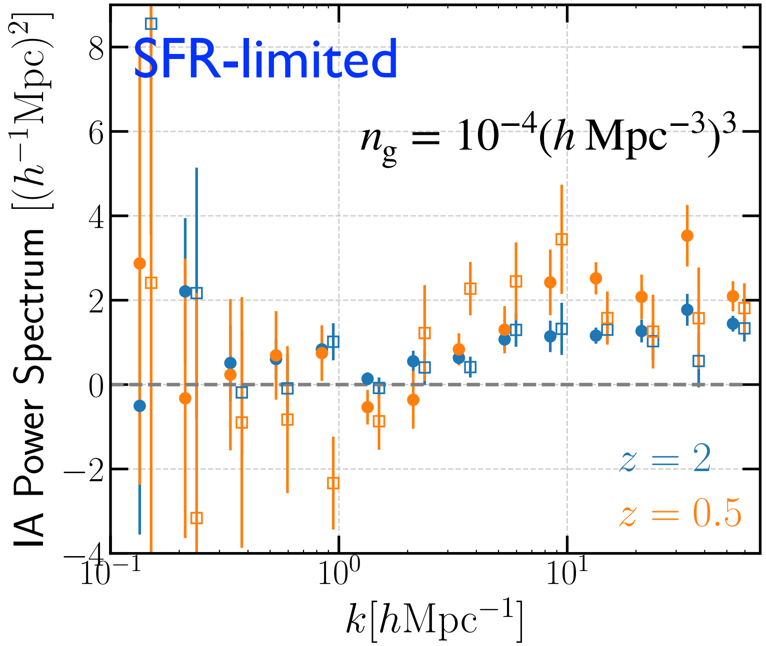
40 x 40 (h^{-1}Mpc)^2

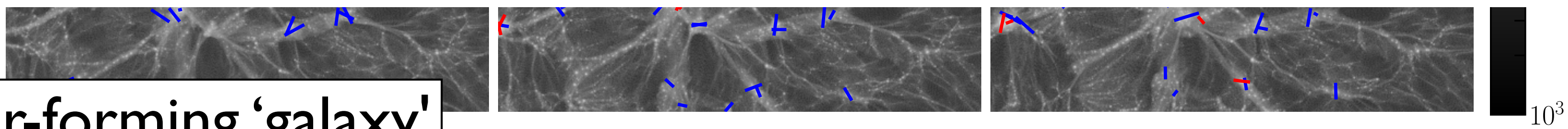
Shi et al. ('20)



GI correlation (power spectrum)







Blue: star-forming 'galaxy'

Red: quiescent 'galaxy'

Blue seems to be randomly oriented

Mechanisms of IA correlation

Tidally induced alignment

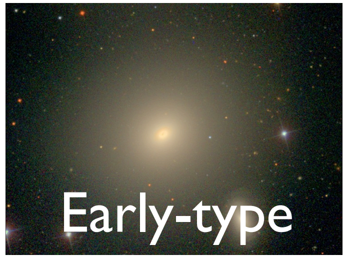
aligned along the tidal field induced by large-scale structure

$$\gamma_a^{\mathrm{I}} \propto \partial^2\Phi$$

Gravitational potential

Determined by large-scale structure

Strong correlation



Spin-induced alignment

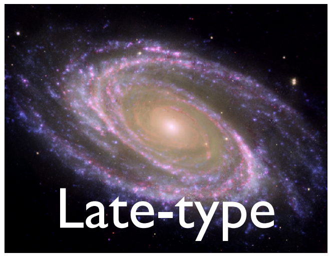
aligned along the acquired angular momentum direction

$$\gamma_a^{\mathrm{I}} \propto \hat{J}^2$$

(Normalized) angular momentum

Determined mainly by local physics

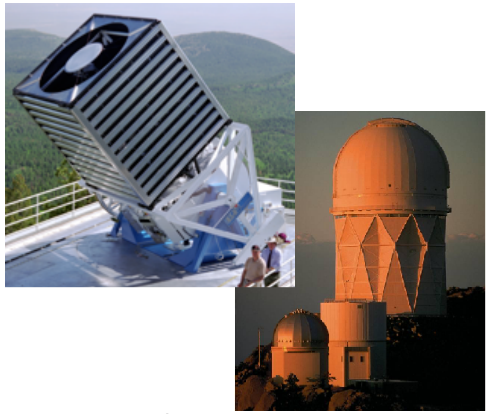
Weak correlation



Cosmology with IA

Tidally-induced IAs look promising and measuring these can have a potential to improve cosmological constraints

Relevant surveys:



Done BOSS† LOWZ ($z \sim 0.3$) & CMASS ($z \sim 0.5$)

Done eBOSS* LRG ($0.6 \le z \le 1$)

Ongoing DESI★ LRG ($0.6 \le z \le 1.2$)

† Baryon Oscillation Spectroscopic Survey

* extended Baryon Oscillation Spectroscopic Survey

★ Dark Energy Survey Instrument

Q

- How well one can model/predict IA correlations ?

  GI & II correlations: $\langle \delta_{\rm g} \gamma_a^{\rm I} \rangle$, $\langle \gamma_a^{\rm I} \gamma_b^{\rm I} \rangle$ $(a, b = +, \times)$

- Combining IAs with conventional GG correlation, how well one can improve the cosmological constraints ?

Linear alignment (LA) model

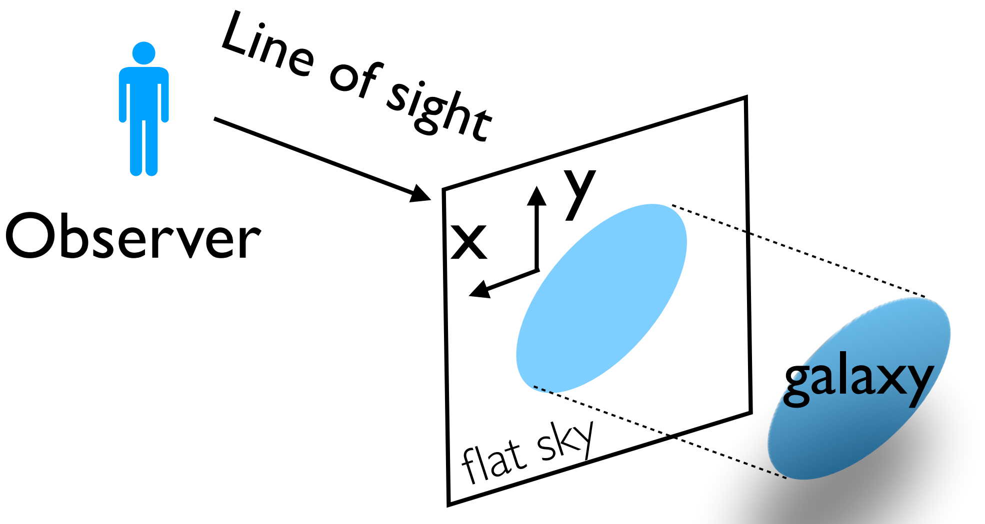
For cosmological purpose,

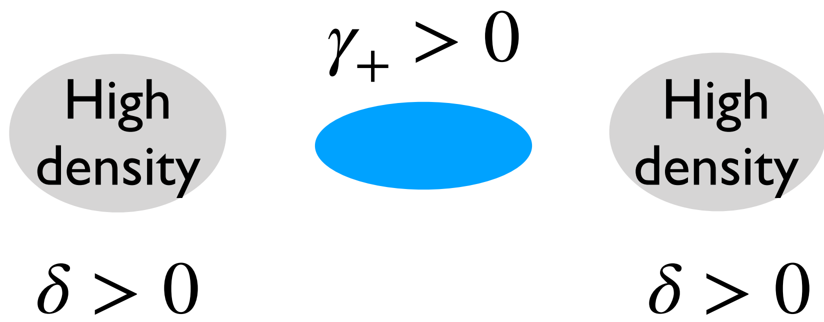
Observing IA of early-type galaxies looks very interesting

<u>A model for tidally-induced IA</u> (Catelan et al. '01, Hirata & Seljak '04)

$$(\gamma_{+}^{\mathrm{I}}, \gamma_{\times}^{\mathrm{I}}) \propto -(\nabla_x^2 - \nabla_y^2, 2\nabla_x\nabla_y)\Phi$$

Gravitational potential



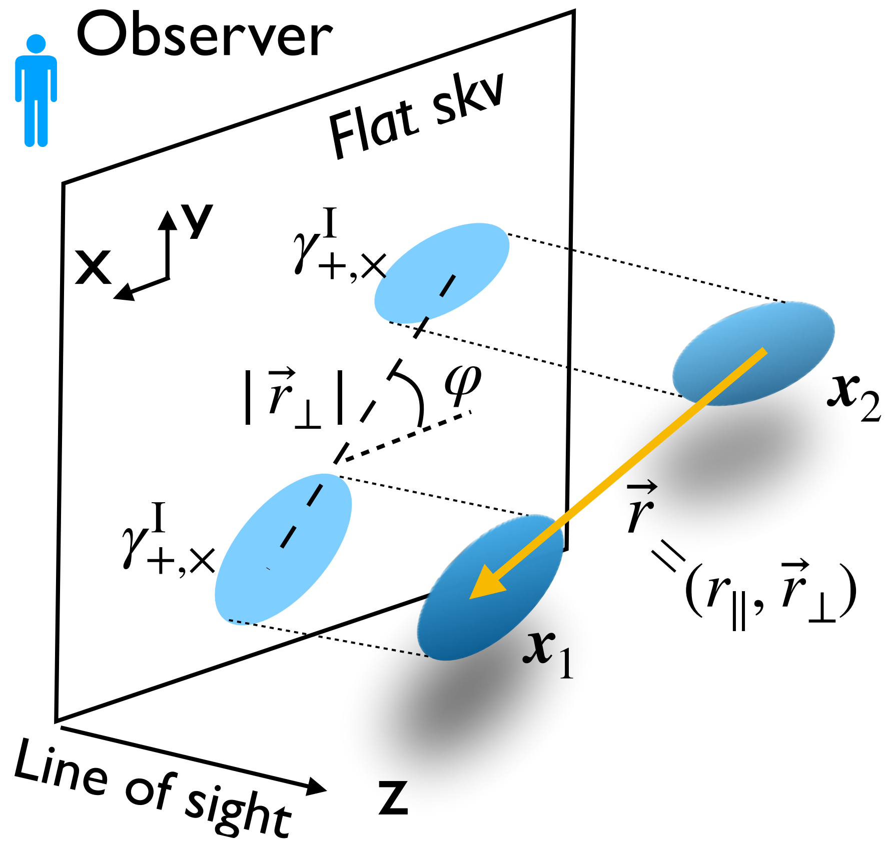


In galaxy redshift surveys, one can measure 3D spatial correlation

IA statistics in 3D

II correlation

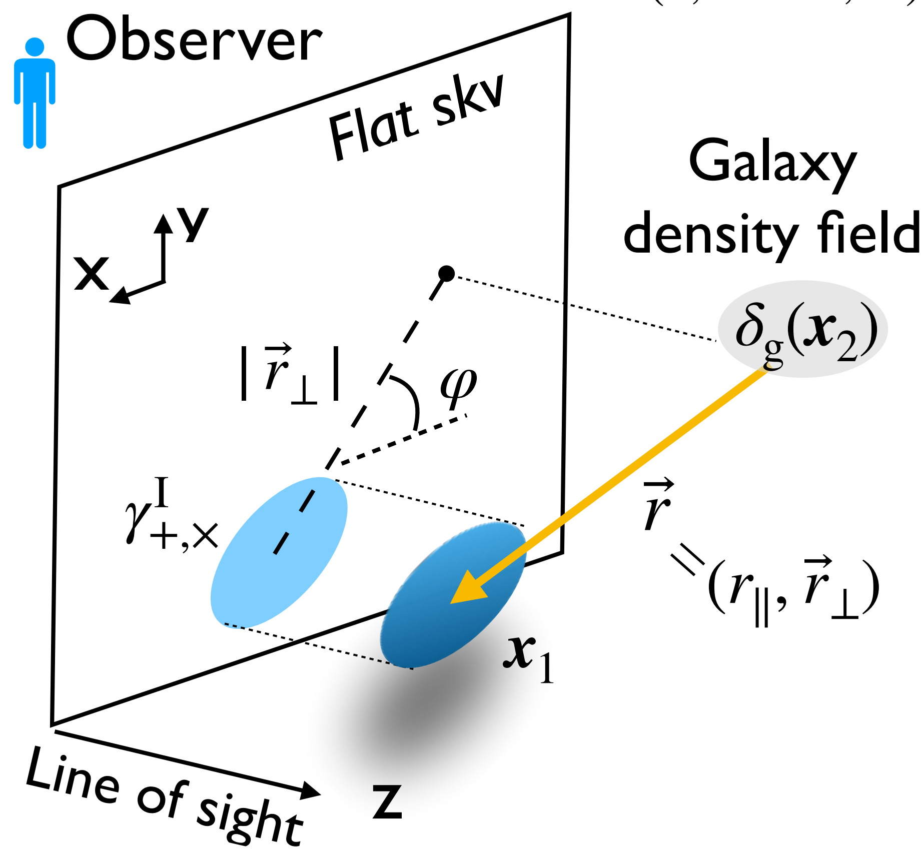
$\xi_{ab} \equiv \langle \gamma^{\rm I}_a(\boldsymbol{x}_1)\gamma^{\rm I}_b(\boldsymbol{x}_2)\rangle$



GI correlation

$\xi_{{\rm g},a} \equiv \langle \delta_{\rm g}(\boldsymbol{x}_1)\gamma^{\rm I}_a(\boldsymbol{x}_2)\rangle$

$(a, b = +, \times)$



With the IA defined by *projected* shape, their correlation becomes *anisotropic* along line of sight, characterized as a function of $(r_\parallel, r_\perp)$

Anisotropic GI & II correlations

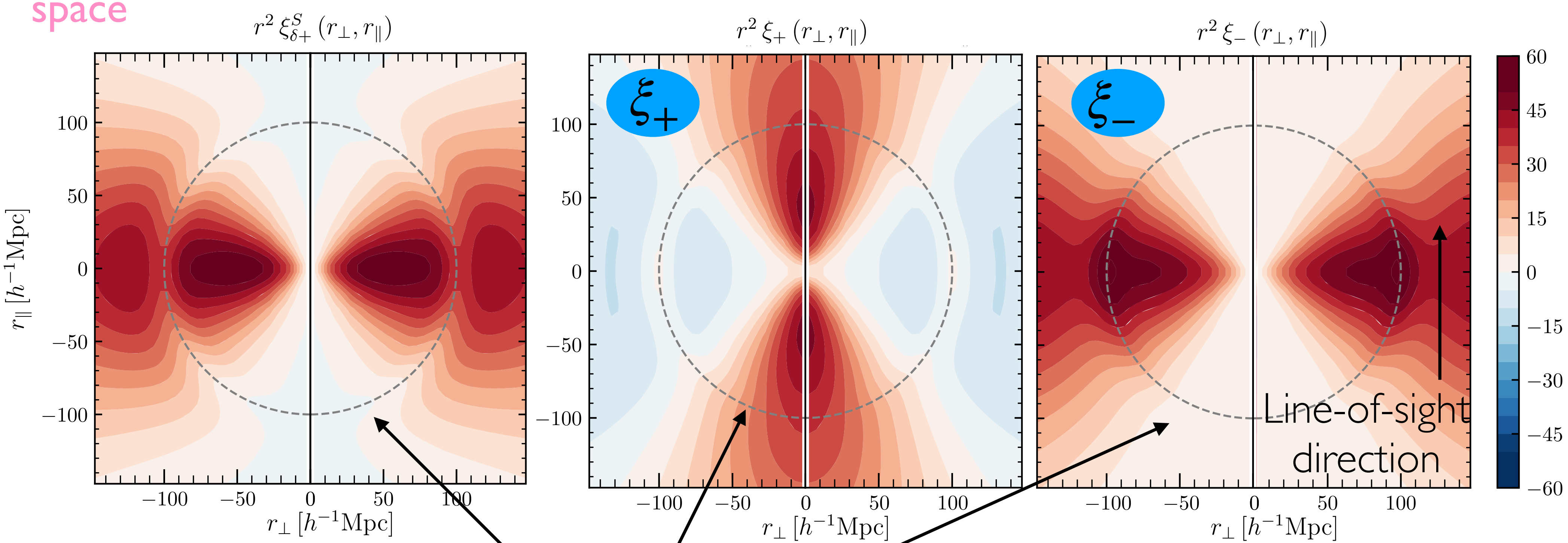
They are given as function of $(r_\perp, r_\parallel)$

Okumura & AT ('20)

Redshift space

GI correlation

II correlation $(\xi_\pm \equiv \xi_{++} \pm \xi_{\times\times})$



Baryon acoustic oscillation feature (appears as 'bump')

$r_\parallel$: line-of-sight separation

Analytical formulas

Okumura & AT ('20)

GI correlation

$\mu \equiv r_{\parallel}/r$

ϕ :azimuthal angle in $\vec{r}_{\perp}$

$$\xi^{R}_{g+}(\mathbf{r}) = \widetilde{C}_1 b_g \cos(2\phi)(1-\mu^2)\Xi^{(0)}_{\delta\delta,2}(r)$$

Real space

$$\xi^{S}_{g+}(\mathbf{r}) = \xi^{R}_{g+}(\mathbf{r}) + \frac{1}{7}\widetilde{C}_1 f \cos(2\phi)\left(1-\mu^2\right)\left[\Xi^{(0)}_{\delta\Theta,2}(r) - \left(7\mu^2-1\right)\Xi^{(0)}_{\delta\Theta,4}(r)\right]$$

Linear growth factor

Redshift space

II correlation

$$\xi_{+}(\mathbf{r}) = \frac{8}{105}\widetilde{C}_1^2\left[7\,\mathcal{P}_0(\mu)\,\Xi^{(0)}_{\delta\delta,0}(r) + 10\,\mathcal{P}_2(\mu)\,\Xi^{(0)}_{\delta\delta,2}(r) + 3\,\mathcal{P}_4(\mu)\,\Xi^{(0)}_{\delta\delta,4}(r)\right]$$

$$\xi_{-}(\mathbf{r}) = \widetilde{C}_1^2 \cos(4\phi)\left(1-\mu^2\right)^2\,\Xi^{(0)}_{\delta\delta,4}(r)$$

$$= \frac{8}{105}\widetilde{C}_1^2 \cos(4\phi)\,[7\,\mathcal{P}_0(\mu) + 10\,\mathcal{P}_2(\mu) + 3\,\mathcal{P}_4(\mu)]\,\Xi^{(0)}_{\delta\delta,4}(r)$$

Expressions are identical in both real & redshift space

$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^{\infty} \frac{k^{2-n}\mathrm{d}k}{2\pi^2} P_{XY}(k) j_\ell(kr)$$

$\mathcal{P}_\ell(\mu)$:Legendre polynomials

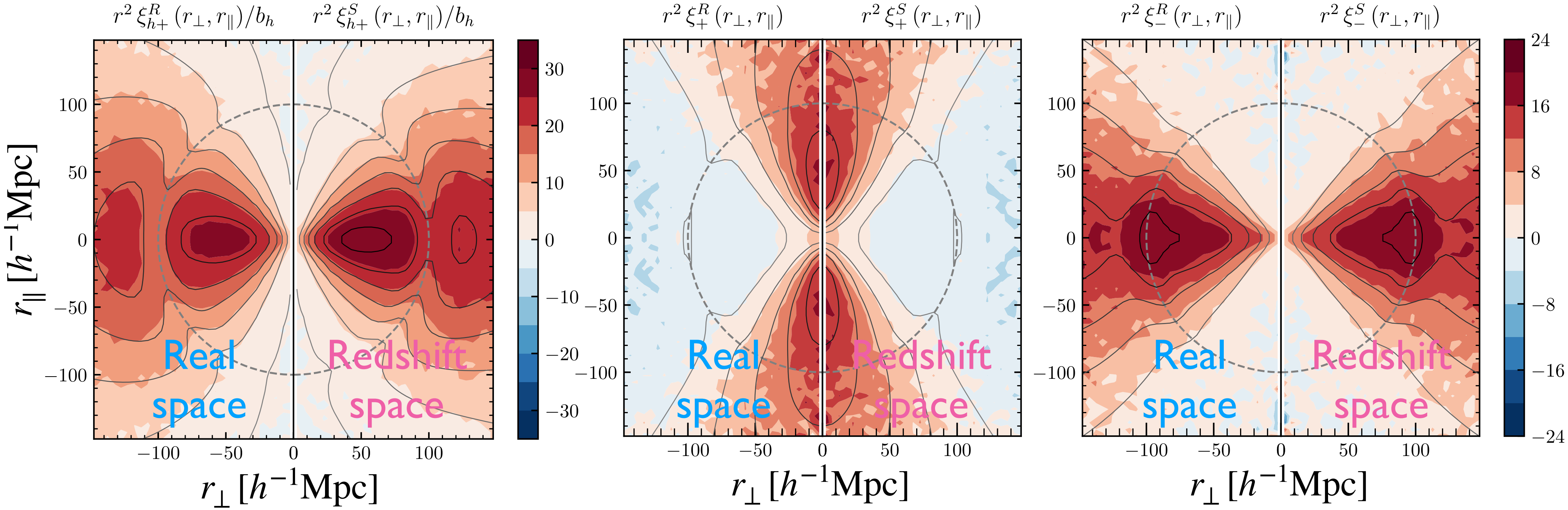
Testing LA model predictions

Okumura, AT & Nishimichi ('20)

GI & II correlations measured @ z=0.3 from (sub-)halo catalog in N-body simulations

GI correlation

ξ_+ II correlation ($\xi_\pm \equiv \xi_{++} \pm \xi_{\times\times}$) ξ_-



$M_\mathrm{h} \geq 10^{13}\,h^{-1}\,M_\odot$

Solid contours: LA model prediction

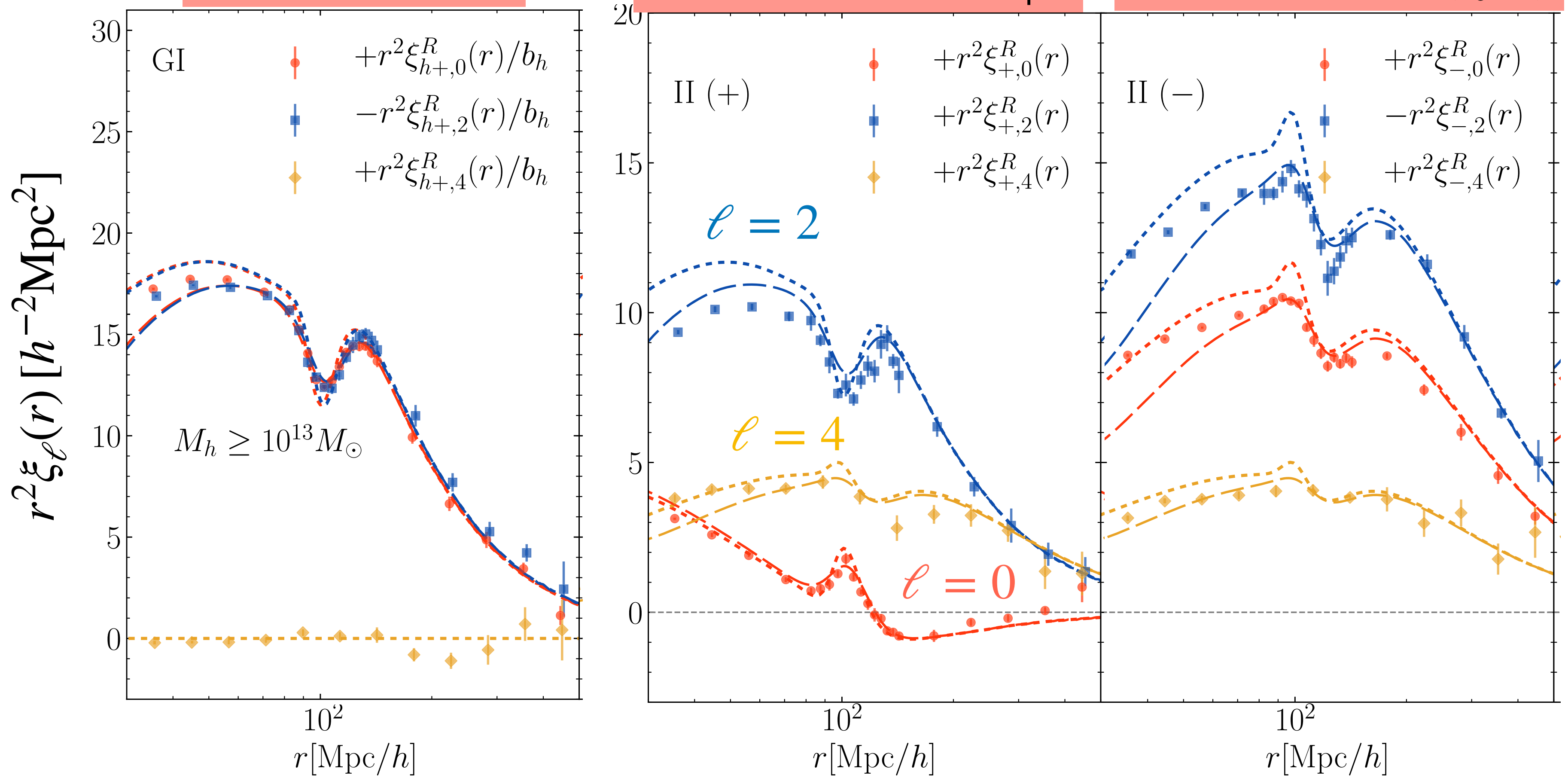
Testing LA model predictions

Okumura, AT & Nishimichi ('20)

Real space

Multipole expansion $\xi(\boldsymbol{r}) = \Sigma_\ell\ \xi_\ell(r)\,\mathscr{P}_\ell(r_\parallel/r)$

GI correlation | II correlation (ξ_+) | II correlation (ξ_-)



dashed : LA model with non-linear P(k), dotted : LA model with linear P(k)

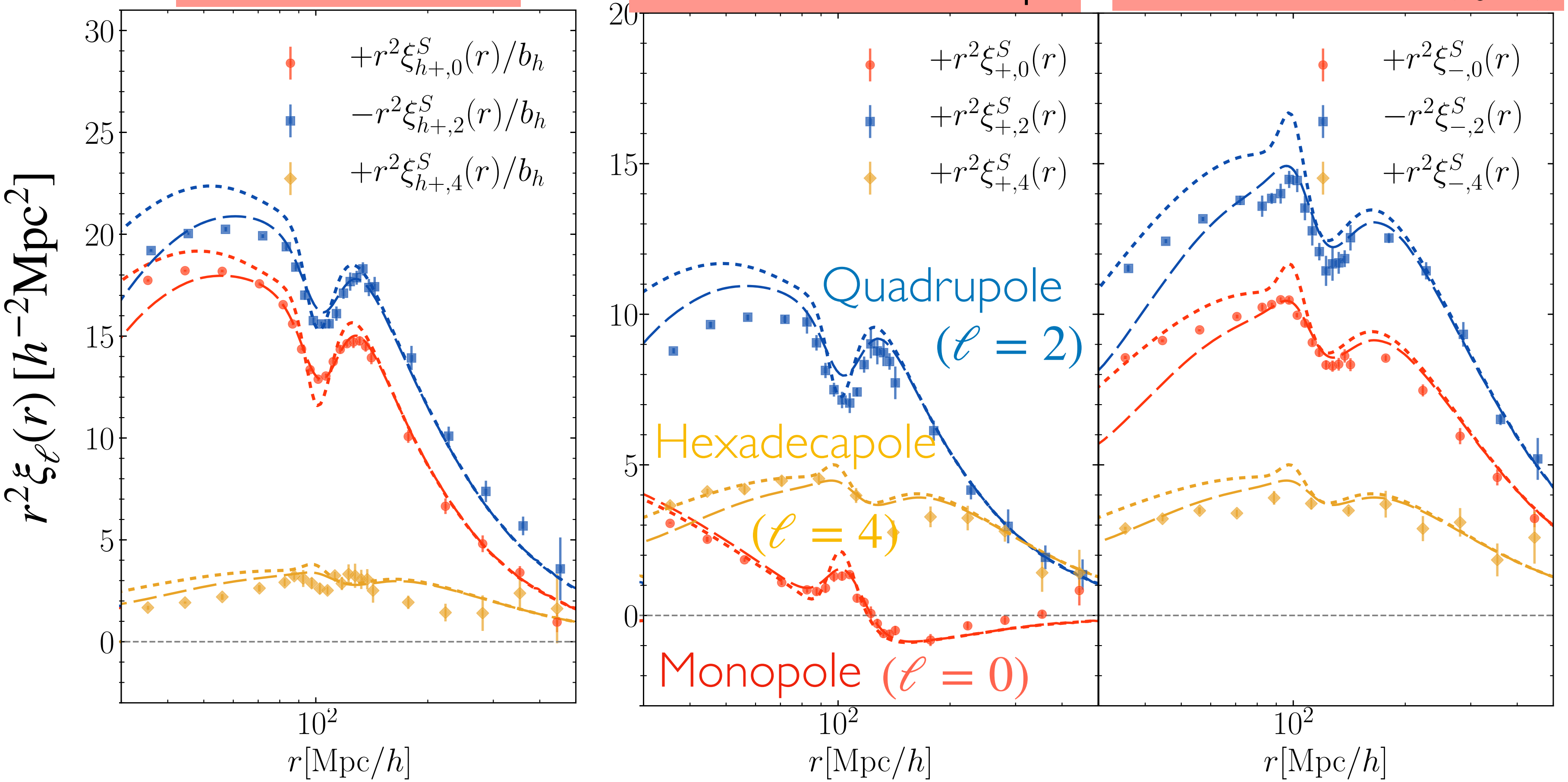
Testing LA model predictions

Okumura, AT & Nishimichi ('20)

Redshift space

Multipole expansion $\xi(\boldsymbol{r}) = \Sigma_\ell \, \xi_\ell(r) \, \mathcal{P}_\ell(r_\parallel/r)$

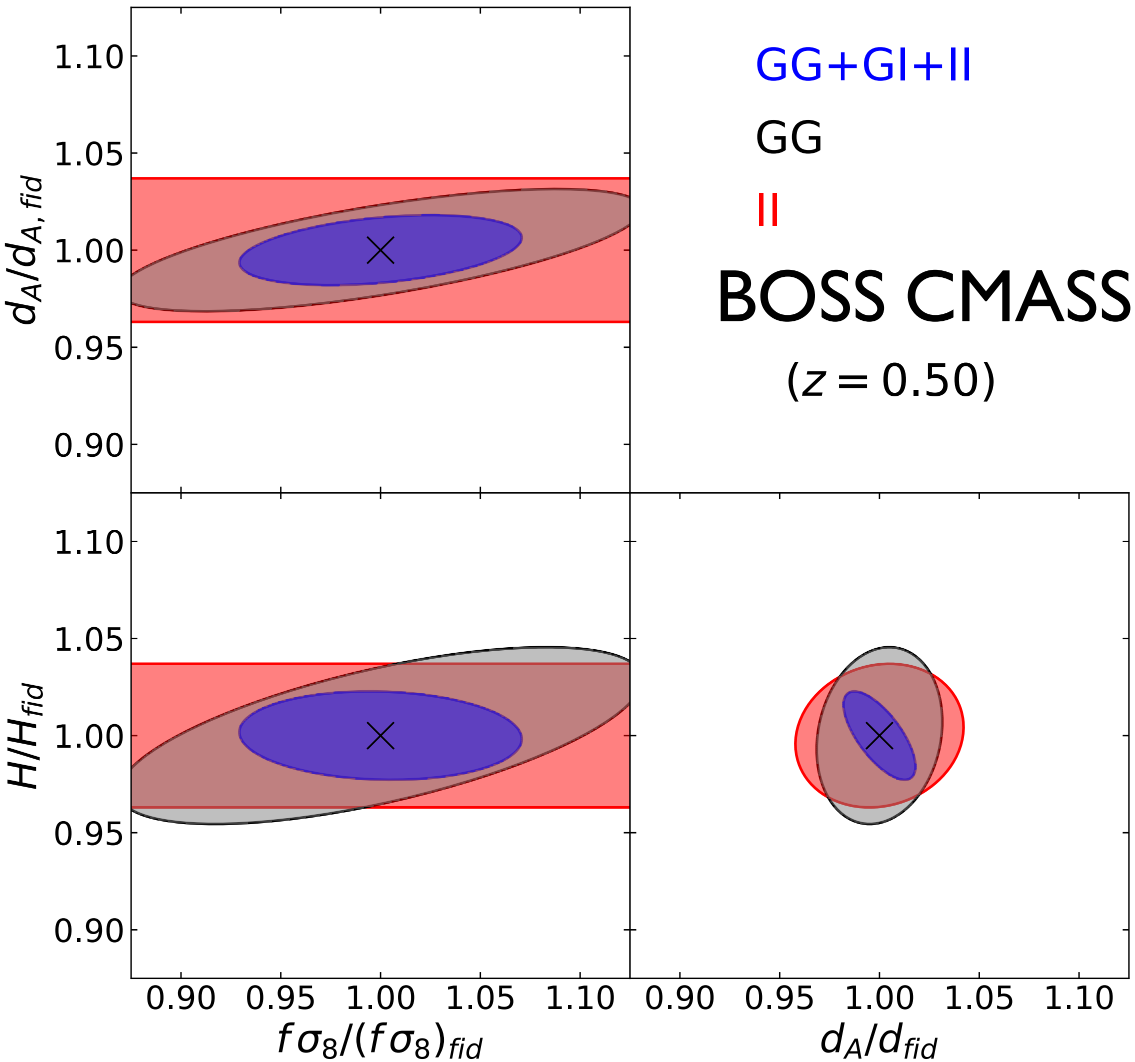
GI correlation | II correlation (ξ_+) | II correlation (ξ_-)



dashed : LA model with non-linear P(k), dotted : LA model with linear P(k)

Geometric & dynamical constraints

RSD & BAO can be measured from GI & II correlations → $\{d_\mathrm{A}(z_i), H(z_i), f\sigma_8(z_i)\}$



GG : galaxy clustering

II : IA statistics

GG+GI+II : both combined

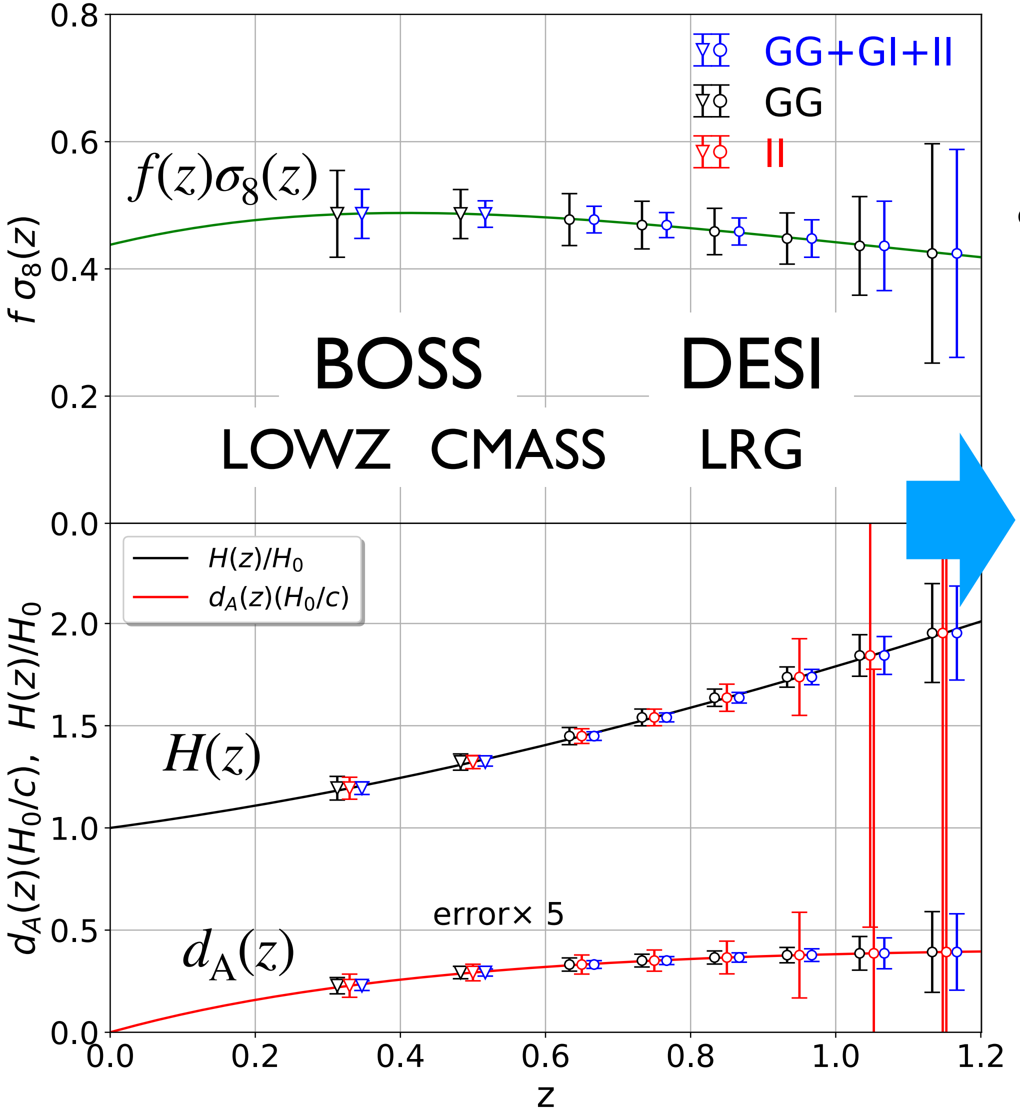
AT & Okumura ('20)

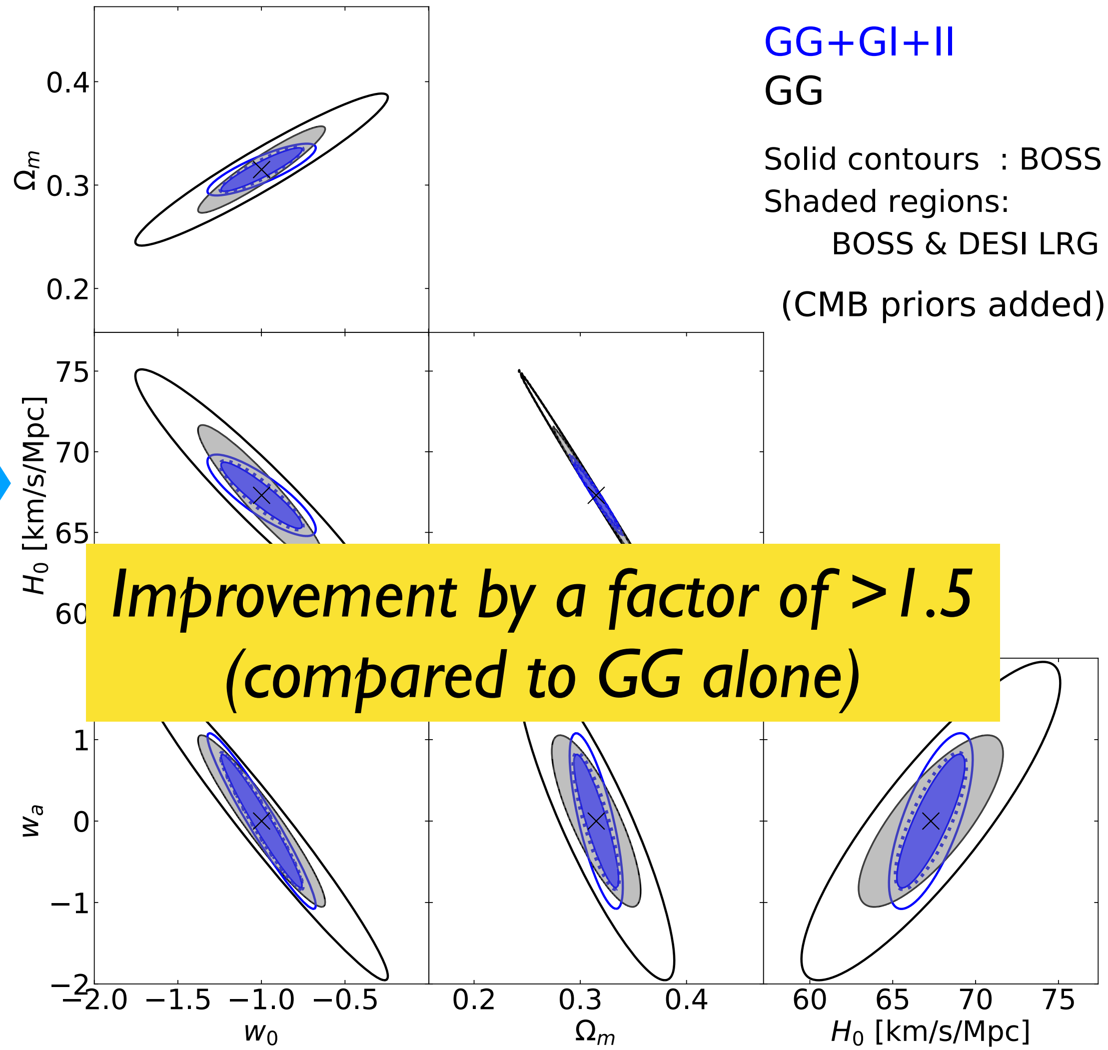
arXiv:2001.05962

Fisher forecast

AT & Okumura ('20)

BAO & RSD measurements from BOSS (finished) & DESI (upcoming)





Improvement by a factor of >1.5 (compared to GG alone)

IA as a promising early-universe probe

In contrast to galaxy density field given as a scalar quantity,

IA is given as a tensor field, and thus can be a sensitive probe to what is difficult to detect with galaxy density field

Anisotropic primordial non-Gaussianity (PNG)

Endlich et al. ('13), Shiraishi et al. ('13), Arkani-Hamed & Maldacena ('15), Lee et al. ('16)

Primordial potential

$$\Phi(\mathbf{x}) = \underbrace{\phi(\mathbf{x})}_{\text{Gaussian}} + \frac{2}{3} f_{\rm NL}^{s=2} \sum_{ij} \underbrace{\left[(\psi_{ij})^2(\mathbf{x}) - \langle (\psi_{ij})^2 \rangle \right]}_{\text{(Gaussian)}^2}$$

$$\psi_{ij}(\mathbf{x}) \equiv \frac{3}{2}\left[\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right]\phi(\mathbf{x})$$

IA field

$$\longrightarrow \gamma_{ij}(\mathbf{k}) \simeq \left[b_K + 12 b_\psi f_{\rm NL}^{s=2} \mathcal{M}^{-1}(k) \right] (\hat{k}_i \hat{k}_j - \delta^{\rm K}_{ij}/3)\, \delta(\boldsymbol{k})$$

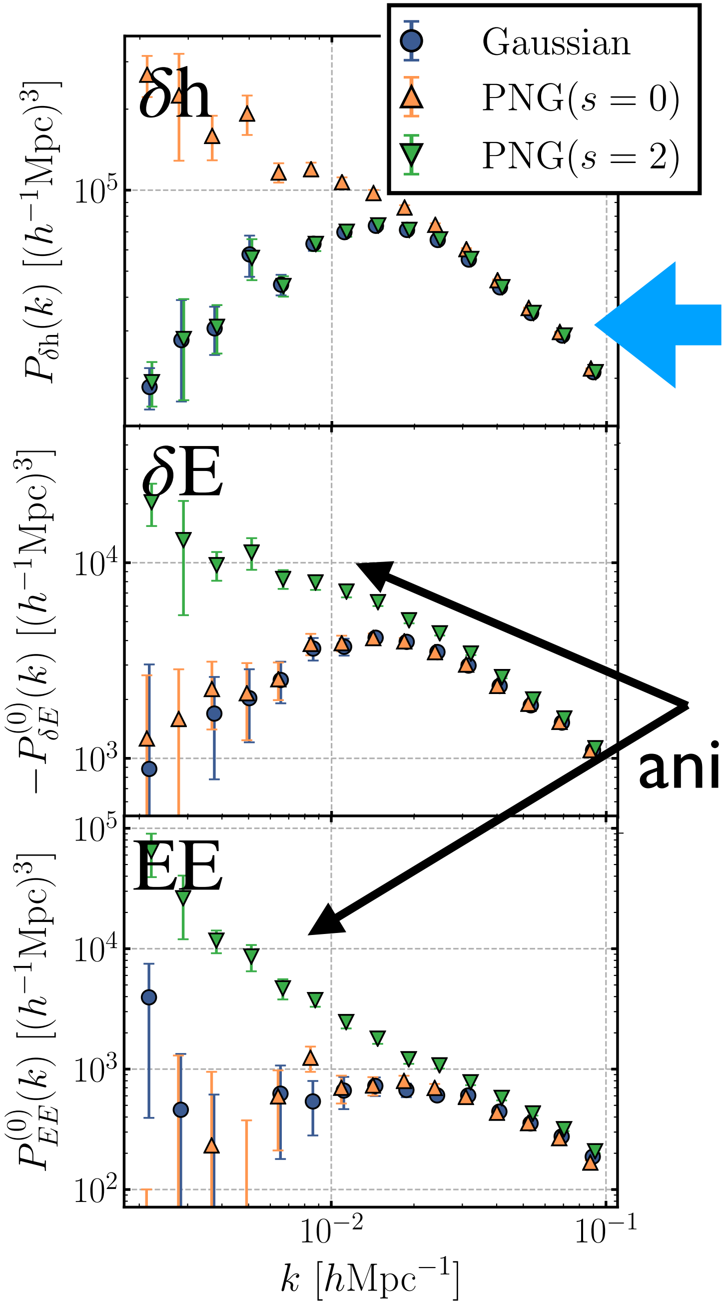
$\propto k^{-2}$

Large-scale enhancement

Schmidt et al. ('15), Kogai et al. ('18, '20); Akitsu et al. ('20)

Constraining new non-Gaussianity

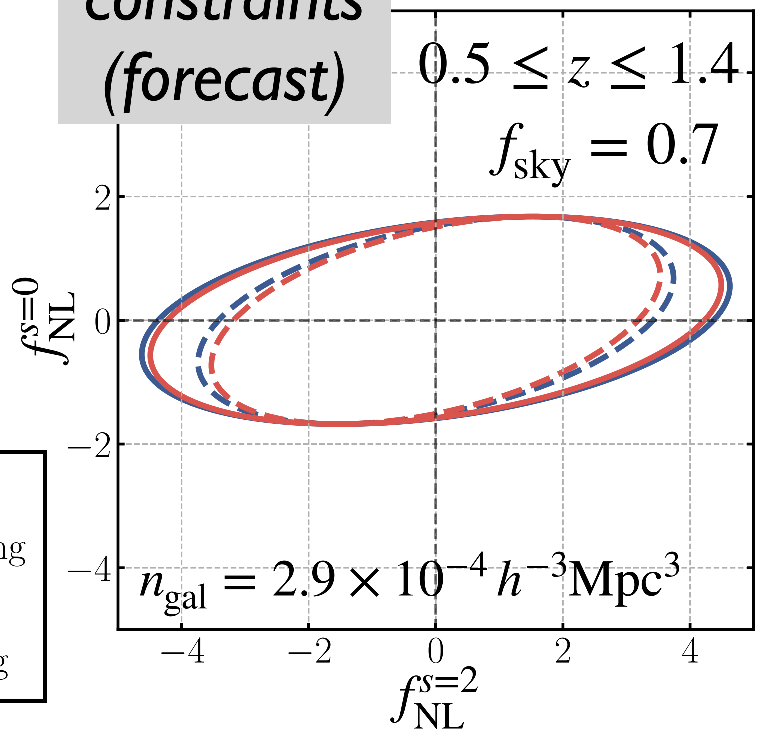
Akitsu et al. PRD
103, 083508 ('20)

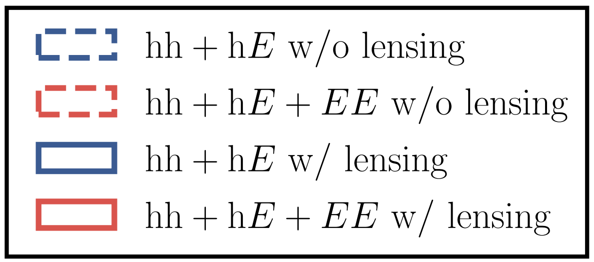


Density field responds to isotropic PNG (s=0)

IA responds to anisotropic PNG (s=2)

Combined constraints (forecast)





Summary

The intrinsic alignment (IA) of galaxies as a novel probe of precision cosmology & early-universe physics

The IA for late-type galaxies can be an ideal tracer of large-scale tidal fields

Linear alignment (LA) model

- accurately predicts large-scale IA correlations (GI & II)
- quantitatively explain anisotropies inherent in 3D correlations

BAO & RSD can be measured

Forecast study with IA correlations

GG+GI+II improves cosmological constraints by a factor of >1.5